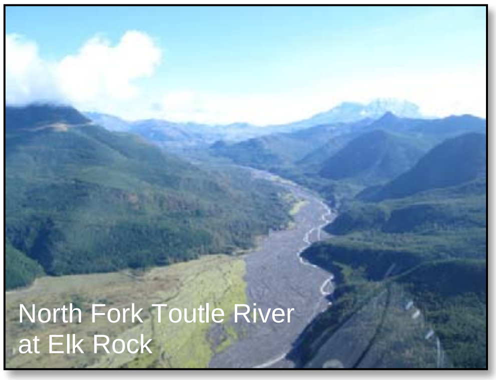
US Army Corps of Engineers ®
Portland District

Biedenharn Group, LLC

Mount St. Helens
Future Expected Deposition Scenario (FEDS)



Channels within the Cowlitz-Toutle Watershed

April 14, 2011

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COMPLETION OF AGENCY TECHNICAL REVIEW

The Agency Technical Review (ATR) has been completed for the Mount Saint Helens Future Expected Deposition Scenario (FEDS) for USAED Portland District. The ATR was conducted as defined in the project's Review Plan to comply with the requirements of EC 1165-2-209. During the ATR, compliance with established policy principles and procedures, utilizing justified and valid assumptions, was verified. This included review of: assumptions, methods, procedures, and material used in analyses, alternatives evaluated, the appropriateness of data used and level obtained, and reasonableness of the results, including whether the product meets the customer's needs consistent with law and existing US Army Corps of Engineers policy. The ATR also assessed the District Quality Control (DQC) documentation and made the determination that the DQC activities employed appear to be appropriate and effective. All comments resulting from the ATR have been resolved and the comments have been closed in DrChecks^{sm}.

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CERTIFICATION OF AGENCY TECHNICAL REVIEW

Significant concerns and the explanation of the resolution are as follows:
The FEDS report introduces the hydraulic and sediment transport tools that will be used to evaluate performance of alternatives for development of a future Mount St. Helens Long Term Sediment Management Plan. The scenario investigated would be the best deterministic estimation of future conditions through the authorization time frame if no actions are taken in the watershed and a continuation of the existing processes and dynamics occur. The FEDS report will be part of a Limited Reevaluation Report.

As noted above, all concerns resulting from the ATR of the project have been fully resolved.

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Executive Summary

This Future Expected Deposition Scenario (FEDS) report introduces the hydraulic and sediment transport tools that will be used to evaluate performance of alternatives for development of a future Mount St. Helens (MSH) Long Term Sediment Management Plan. The scenario being investigated is the best deterministic estimation of future conditions through the authorization time frame if no actions are taken in the watershed and a continuation of the existing processes and dynamics occur. The FEDS report, along with the *Toutle/Cowlitz River Sediment Budget,* May 18, 2010, and the *2009 Progress Report,* June 2010, will be part of a Limited Reevaluation Report (LRR).

The selected technical approach utilizes a set of deterministic hydraulic and sediment transport models arranged in series extending from the toe of the debris avalanche in the upper North Fork Toutle watershed downstream to the Columbia River. This set of models is driven by a time series of flows and sediment inputs extending from present time to the end of the authorization period, Water Year (WY) 2035. This 28-year series of water and sediment discharges was based on 9 years of historic hydrologic record (WYs 1999 to 2007). Data developed in the Sediment Budget for WYs 1999 to 2007 were used as surrogates for future forecast years through 2035. Analysis of the surrogate hydrologic period compared to the historic flow record shows that the period is reasonably representative of the historic sediment yield record. Considerations of global climate change are not addressed in this analysis due to the relatively near 2035 end-of-project authorization. The total predicted load from the MSH debris avalanche to the Sediment Retention Structure (SRS) sediment plain for the period from 2008 to 2035 is estimated to be 215 M Tons.

Sediment transport models using both 1-D HEC-RAS and 2-D MIKE 21C software were developed to determine future trends in sediment deposition and outflow from the SRS through 2035. The 1-D and 2-D model limits extend approximately 9 miles upstream from the SRS spillway to just upstream of N1. Both models were calibrated to historic observed deposition and run for a specific 28-year future sequence of surrogate years. Results from both long-term models generally agree providing additional certainty in the analysis; however, sediment output from the 2-D model is considered most accurate due to the improved capability to analyze hydraulic conditions in a braided system by the 2-D model. Sediment loading output from the 2-D model is used in downstream models. Annual trap efficiency of the SRS through 2035 is highly variable; however, the cumulative trap efficiency shows a declining trend. The overall trapping efficiency above the SRS over the 28-year simulation from 2-D results was computed to be 20%. The trapping efficiency computed by the Sediment Budget between 1999 and 2007 was estimated to be 37%. The total sediment output from the SRS for the 28-year simulation is computed to be 172 M Tons and composed of 25% clay/silt, 72% sands, and 3% very fine gravels.

The Toutle River system below the SRS is a transport reach for sand-sized material that passes through the SRS spillway. Additional sources of sediment are introduced in this reach including the inflow from the Green and South Fork Rivers, and bank erosion throughout the system. Total additional sediment load from the Green and South Fork Rivers and other sources for the forecast sequence through 2035 is estimated to be 30.9 M Tons, which is 15% of the total load entering the Cowlitz from the Toutle. Total load to the Cowlitz River from the Toutle between 2008 and 2035 is estimated to be 203 M Tons, composed of 24% clay/silt, 72% sands and 4% gravels.

Depositional trends through the planning period in the lower 20 miles of the Cowlitz River below its confluence with the Toutle River is investigated by sediment transport modeling using 1-D HEC-RAS software. This mobile-bed tool was developed from a hydraulically-calibrated fixed-bed model utilized in the 2009 Level of Protection analysis. The sediment transport function within the model was calibrated to observed depositional trends between 2003 and 2008. The model was then run with the 28-year long-term sequence of flows and sediment loads developed from upstream analysis. Total deposition in the Cowlitz River between the Toutle and the Columbia is estimated to be 37.7 M Tons. Coarse and very coarse sands comprise nearly 80% of the deposited mass.

The confluence of the Cowlitz and Columbia Rivers is a hydraulically-complex tidally-affected area where significant shoaling has been historically observed. A fully-coupled 2-D hydrodynamic model was created of the lower 4.5 miles of the Cowlitz River from just downstream of the Allen Street Bridge to the Cowlitz - Columbia River confluence. The model also includes Carol's Channel and the Columbia River from upstream of Carol's Channel to about a mile downstream of the Cowlitz - Columbia River confluence. Sediment outflow from the Upper Cowlitz River 1-D sediment transport model was added to the 2-D model and a period of representative years from Aug 2004 to Aug 2007 were studied to better understand sedimentation trends and effects on flood stages in the Cowlitz due to shoaling at the mouth in this area with respect to this FEDS study. Excessive run times prevented long-term runs for this model.

With the suite of models described in this report, it is possible to produce a probabilistic levee performance metric for future conditions with and without alternatives. The models can be used to predict future condition stage-discharge rating curves for frequency flows. This can be combined with the existing hydrologic and geotechnical data and analyzed in the Flood Damage Assessment (FDA) tool. This probabilistic future performance metric will be used to determine if a proposed action or suite of actions (alternatives) is viable in protecting the communities. Alternatives moving forward for consideration will need to reasonably meet the performance metric. The approach taken lays the foundation for future plan selection determining alternative parity based on model results. The selected modeling approach provides adequate flexibility to accommodate the full range of proposed actions, while delivering the required high-quality results. Significant findings of the FEDS effort include the following:

- Analysis of SRS future performance indicates that there will be a significant reduction in trapping efficiency of coarse and very coarse sands in the current planning period. Downstream analysis shows that these are the materials that compose the majority of deposition in the lower 20 miles of the Cowlitz in the same time frame.
- Uncontrolled deposition in the lower Cowlitz will affect upstream communities first. Communities higher in the system will experience a reduction in future flood-protection system performance more rapidly than those lower in the system due to this cumulative effect of deposition downstream of their levees.

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Acknowledgements

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1.0 INTRODUCTION

1.1 Background

Following the dramatic eruption of Mount St. Helens on May 18, 1980 and the deposition of approximately 3 billion cubic yards of primarily sand and gravel material in the upper 17 miles of the North Fork of the Toutle River, significant urban and industrial flooding occurred along the lower 20 miles of the Cowlitz River (Major *et al*. 2000; USACE 1984). Subsequent mudflows and sedimentation along the lower Toutle and Cowlitz Rivers from 1981 to 1986 required the investigation and implementation of permanent measures by the U. S. Army Corps of Engineers (USACE) to address the long-term impacts of the Mount St. Helens eruption.

The Mount St. Helens (MSH) Project was formulated to control the movement of large amounts of sediment downstream from the debris avalanche resulting from the eruption and maintain a congressionally authorized level of flood protection for four leveed communities along the lower Cowlitz River. The present Congressional Authorization dates to 1985 and is based on a 50-year project lifetime, extending to 2035. Major actions taken by the USACE following the eruption aimed at maintaining flood protection of these communities include: levee improvements; dredging in the Columbia, Cowlitz, and Toutle Rivers; and construction of the N1 sediment dam, Spirit Lake outlet tunnel, and the Sediment Retention Structure (SRS) on the North Fork Toutle.

Following completion of the SRS construction in 1989, sedimentation trends in the lower Cowlitz River were in relative equilibrium until the SRS began regularly passing water and sediment over the spillway in 1998, significantly reducing trapping efficiency of the structure. The mild deposition trend observed post-filling was punctuated with significant deposition in Water Year (WY) 2007. The increase in sediment transport below the SRS downstream to the Cowlitz River has contributed to increased deposition and decreasing levels of flood protection on the lower 20 miles of the Cowlitz River. Other significant sources of sediment in the Toutle watershed have also been identified as contributing to the overall supply to the Cowlitz River, however, the debris avalanche in the upper North Fork Toutle Basin remains as the dominant source. Figure 1.1 is a vicinity map of the Toutle and Cowlitz Rivers.

A more detailed summary of project history can be found in the *Mount St. Helens Long-Term Sediment Management Plan for Flood Risk Reduction* (2009 Progress Report; USACE 2009a).

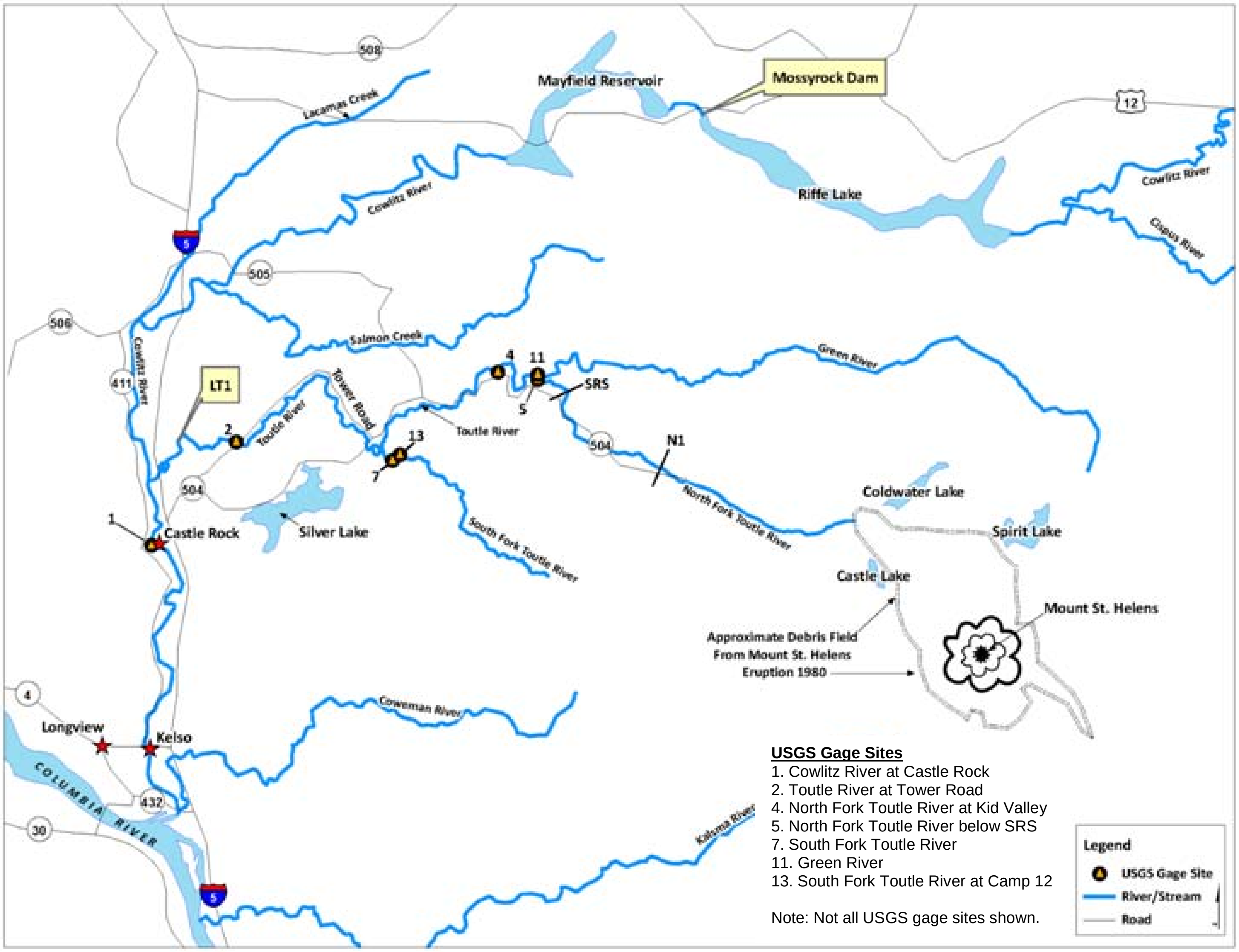

Figure 1.1 Project Vicinity Map

1.2 Purpose

This Future Expected Deposition Scenario (FEDS) report introduces the hydraulic and sediment transport tools that will be used to evaluate alternatives for development of a future MSH Long Term Sediment Management Plan. The scenario being investigated is the best deterministic estimation of future conditions through the authorization time frame if no actions are taken in the watershed and a continuation of the existing processes and natural dynamics occur. While the FEDS is not a viable alternative for meeting authorization requirements, it is important to understand the impact of a no action alternative as an intuitive reference scenario for developing and demonstrating analytic tools.

As the MSH Project is an ongoing construction project with Congressional authorization, the phrases "No Action" and "Existing Condition" are previously defined inside of the planning idiom. Both of these conditions correspond to the authorized plan of action that includes Base-Plus Dredging along the four lower protected communities once the SRS begins passing sediment in problematic quantities. This FEDS report is a construct that allows for a logical starting condition for analytic comparison of alternatives, while still honoring the planning process. The "No Action" scenario of Base-Plus Dredging will be technically investigated in the same manner as alternatives using the models developed in this report.

The FEDS report, along with the *Toutle/Cowlitz River Sediment Budget,* May 18, 2010, and the *2009 Progress Report,* June 2010, will be part of a Limited Reevaluation Report (LRR). This interim report is produced to gain certainty in the selected technical approach early in the study. While the basic tools used are not new, the complexity of the interdependent 28-year simulations need to be validated before utilizing the base models in alternative analyses. This FEDS report serves to validate the long-term models in a technically reviewed document separate from final alternative analyses.

1.3 Methodology/Selected Approach

The selected approach utilizes a set of deterministic hydraulic and sediment transport models arranged in series extending from the toe of the debris avalanche in the upper North Fork Toutle watershed downstream to the Columbia River. This set of models is driven by a time series of flows and sediment inputs extending from present time to the end of the authorization period, WY 2035. Selection of the time series is based on historical data and attempts to represent mean conditions. From the selected approach, a performance metric can be developed that relates to the project authorization and can be utilized to determine feasibility of alternatives during plan formulation.

The study area can be broken into five distinct regions based on geomorphic processes and hydrologic trends. Analytic tools described within this report correspond to these boundaries

(Figure 1.2). A flow chart following the sediment load through the selected approach is shown in Figure 1.3. Table 1.1 provides a list of developed models, the extents, simulation time period, and purpose. This report relies heavily on work presented in the *Toutle/Cowlitz River Sediment Budget* (dated May 18, 2010; Biedenharn Group, LLC 2010). Familiarity with that document will be necessary to fully understand all inputs to the FEDS modeling.

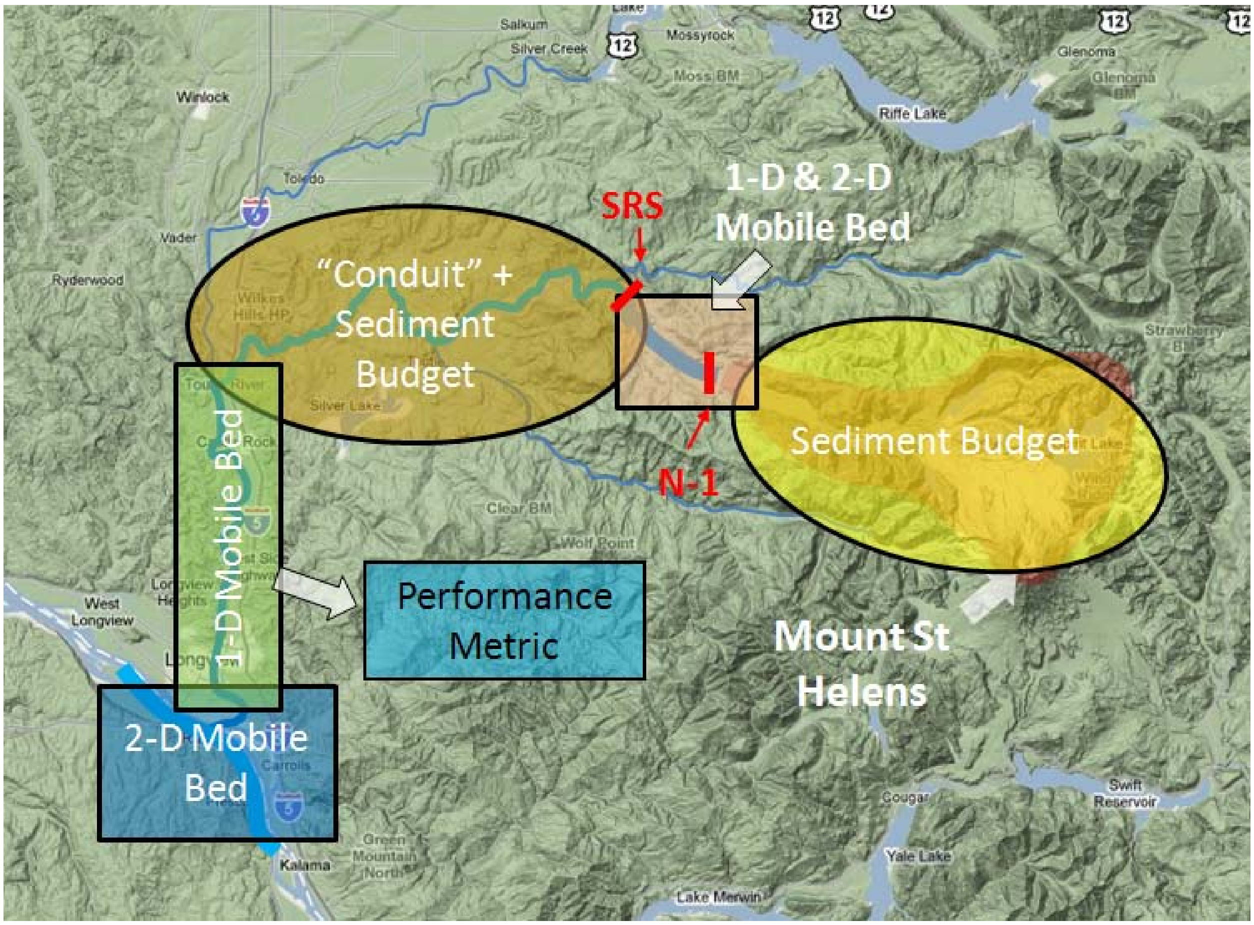

Figure 1.2 Selected Approach

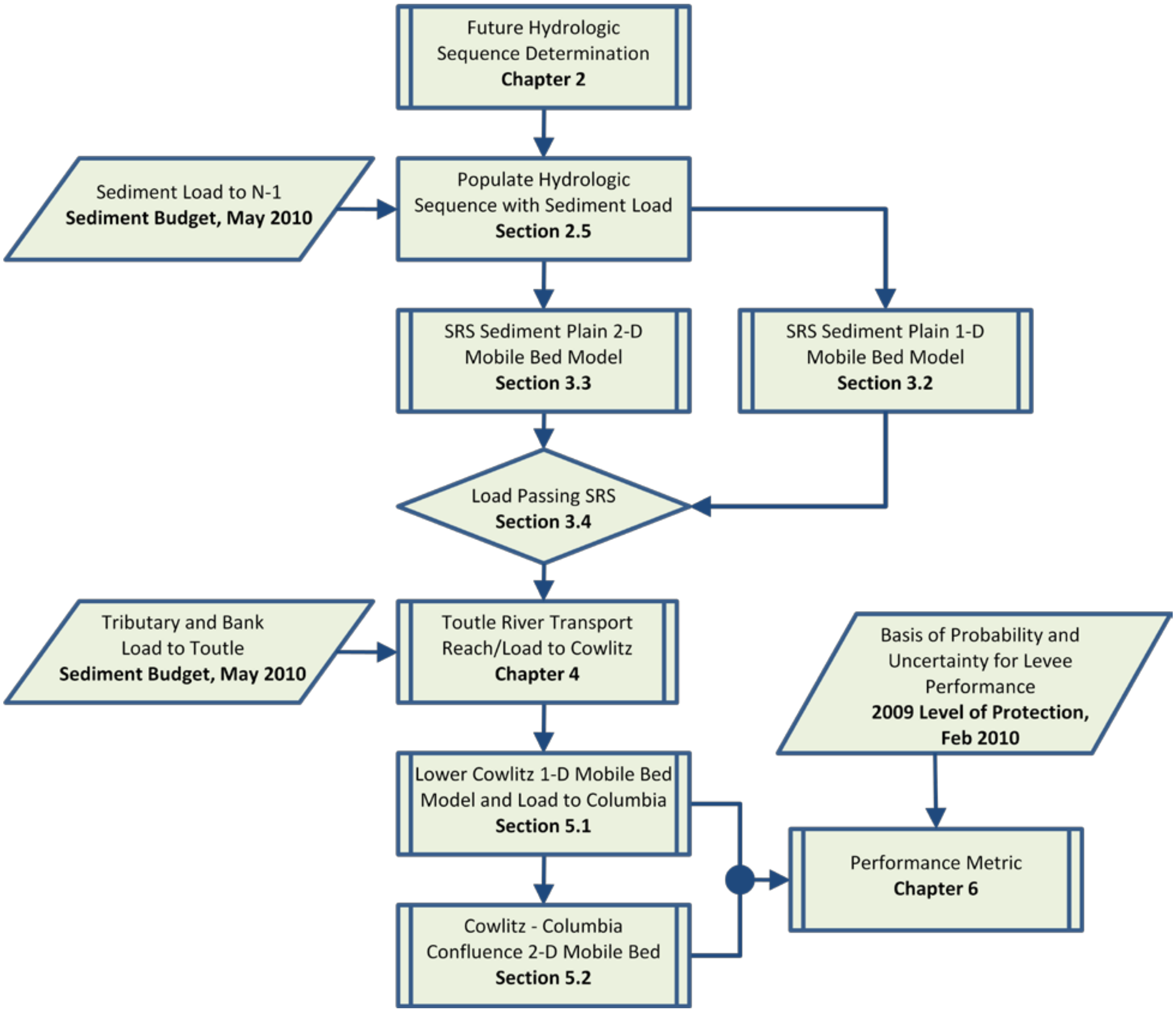

Figure 1.3 Flowchart of Selected Approach for Long-term Runs

Table 1.1 List of Models

River	Reach	Model [A]	Time Period	Purpose
North Fork, South Fork, Toutle, and Cowlitz Rivers	Debris Avalanche to Columbia River	Sediment Budget Spreadsheet Model	1999 – 2007 (9 years)	Identify existing sediment sources/sinks in Toutle/Cowlitz watershed. Utilized to develop input and calibration data for other models.
North Fork Toutle	N1 to SRS	1-D HEC-RAS	Oct 2003 – Sep 2006 (3 years)	Calibration Model
North Fork Toutle	N1 to SRS	1-D HEC-RAS	Oct 2007 – Sep 2035 (28 years)	Forecast model to predict trends in sediment deposition and output by 2035. Will be used to test proposed measures where appropriate.
North Fork Toutle	N1 to SRS	2-D MIKE 21C	Oct 2003 – Sep 2006 (3 years)	Calibration Model
North Fork Toutle	N1 to SRS	2-D MIKE 21C	Oct 2007 – Sep 2035 (28 years)	Forecast model to predict trends in sediment deposition and output by 2035. Output passed down to Cowlitz 1-D/2-D modeling. Will also be used to test proposed measures where appropriate.
Cowlitz River	Toutle to Columbia	1-D HEC-RAS	Aug 2004 – Sep 2008 (6 years)	Calibration Model
Cowlitz River	Toutle to Columbia	1-D HEC-RAS	Oct 2007 – Sep 2035 (28 years)	Forecast to predict trends in deposition in Cowlitz River. Will be used to test proposed measures.
Cowlitz River	Lower 4 Miles	2-D MIKE 21C	Aug 2004 – Aug 2007	Short-term model developed for analysis of proposed measures.

[A] MIKE 21C (DHI; http://www.mikebydhi.com/) and the updated (Beta) Version 4.1 of the USACE's HEC-RAS (Hydrologic Engineering Centers River Analysis System, USACE; http://www.hec.usace.army.mil/software/hec-ras/) software

A brief description of each reach and tool applied follows:

1. North Fork Toutle River, above the remnant N1 Structure. This is the Debris Avalanche Zone and the primary source of sediment to the Toutle watershed and lower Cowlitz River. Data from the *Toutle/Cowlitz River Sediment Budget* (dated May 18, 2010; Biedenharn Group, LLC 2010; hereafter referred to as the 2010 Sediment Budget Report (2010 SBR)) are used to represent this zone and drive the sediment load to the models below.
2. North Fork Toutle River, sediment plain above the SRS and below N1. The North Fork Toutle River above the SRS is a wide braided sediment plain formed by construction of the structure and remains a significant sediment sink in the system. Both one-dimensional (1-D) and two-dimensional (2-D) mobile-bed models were developed for this area.
3. Toutle River watershed below the SRS. Field observation indicates that the Toutle River system below the SRS is a transport reach for sand-sized material that passes the SRS. Additional sources of sediment are introduced in this reach including the Green River, South Fork of the Toutle River, and bank erosion throughout the system. A spreadsheet analysis, using outputs from upstream models along with the Sediment Budget and U.S. Geological Survey (USGS) suspended sediment gage data, is used is this area.
4. Cowlitz River below the Toutle River. The four communities protected by federally inspected levees forming the basis of the MSH Project authority lie along the lower 20 miles of the Cowlitz River below the confluence with the Toutle River. This reach receives the majority of water from the upper Cowlitz Basin and nearly all of the sediment supply from the Toutle River. Level of protection for these communities is affected by an aggradational trend in this reach. A 1-D mobile-bed model is utilized for this reach.
5. Confluence of the Cowlitz and Columbia Rivers. The Columbia River and lower 5 miles of the Cowlitz River are tidally affected and hydraulically complex. A 2-D mobile-bed model is applied in this reach.

The primary sediment supply to the Toutle River comes from the non-linear channel network evolution of the debris avalanche from the May 1980 eruption of MSH. Standard watershed analysis stationarity assumptions can be both conservative and non-conservative in terms of protection to the communities along the lower Cowlitz River. In the time frame of the analysis (approximately 28 years into the future) some trends may have little effect and can be discounted for the lack of data or science without significantly skewing the results. In the conservative camp these include decay in debris avalanche sediment output, vegetation of the debris avalanche and/or sediment plain, and decrease in hydrologic productivity. The non-conservative minor trends for the time frame include climate change. The selected approach aims to address the major non-conservative trend of the SRS trapping efficiency decay, while applying the stationarity assumption where the expected impact of change is small or conservative.

Variability is addressed in the selected approach by utilizing all historic data that represents current conditions, WYs 1999 through 2007. The rapid changes in the system and the lack of an analog for correlation and extension of the data complicate assessing how the observed variability ranks with all variability.

Any selected analytic scheme has advantages and limitations. The selected approach attempts to utilize the most appropriate modeling tools for each reach; however, all phenomena related to sediment and hydrology in the system cannot be fully addressed. The significant advantages and limitations of the selected approach are presented below:

Advantages

1. Calibration. Sufficient data exist in each major reach to allow for calibration of hydraulic and sediment transport models. Separating the reaches based on geomorphic trends allowed each modeled reach to be more accurately calibrated in lieu of applying a general transport equation to the entire basin.
2. Appropriate model use. The selected approach uses the appropriate tool for each reach of the study. Two-dimensional hydraulic models are used where averaging cross section hydraulic parameters was not appropriate. Spreadsheet tabulation was used in some reaches where effects of backwater and hydraulic routing are minimal. Tailoring the modeling approach to specific reaches generally simplifies the computations.
3. Applicability to alternative analysis. The selected approach provides appropriate tools for analyses of the list of alternatives presented in the *Mount St. Helens Long-Term Sediment Management Plan for Flood Risk Reduction* (2009 Progress Report; USACE 2009a).
4. Applicability to authority. The performance metric generated from the selected approach relates directly to the Congressional Authorization.

Limitations

1. The Toutle River and North Fork Toutle River below the SRS are analyzed as transport reaches. All annual load entering the reach exits to the Cowlitz in the same water year. There is no evidence of significant storage in this reach of the Toutle River, however, the potential for sediment lag not observed in the historic record exists and is not included in the FEDS analysis.
2. Complexity of the approach. Complexity of the analyses limits the number of scenarios that can be modeled and forces a deterministic approach.
3. No debris avalanche decay. It is expected that decay of debris avalanche erosion will occur in the long term, however, it is expected that we are in a current state of quasi-equilibrium for the study period. Currently definitive evidence of decay of debris avalanche erosion has not been proven or disproven. This is the least understood and most conservative assumption.
4. Inputs limited to observed data. Rapid evolution of processes and a lack of an analog system limit inputs to data observed in the current condition. This may skew

the results in terms of mean and variability; however, synthetic inputs would have unacceptably high uncertainty.

5. Hydrologic stationarity. Representation and prediction of forecast years using historic data as a surrogate assumes that historic rainfall runoff relationships and climate data will persist into the future.
6. No allowance for very rare events. There are several possible and potentially catastrophic future events that this analysis does not attempt to address including but not limited to volcanic eruption, lake breakout, and extreme hydrologic events.

2.0 HYDROLOGY

2.1 Background

Hydrologic input required for sediment modeling was developed using daily average discharge data obtained from USGS gage sites located throughout the Toutle/Cowlitz watershed. Locations of current and historic USGS gage sites are illustrated in Figure 2.1.

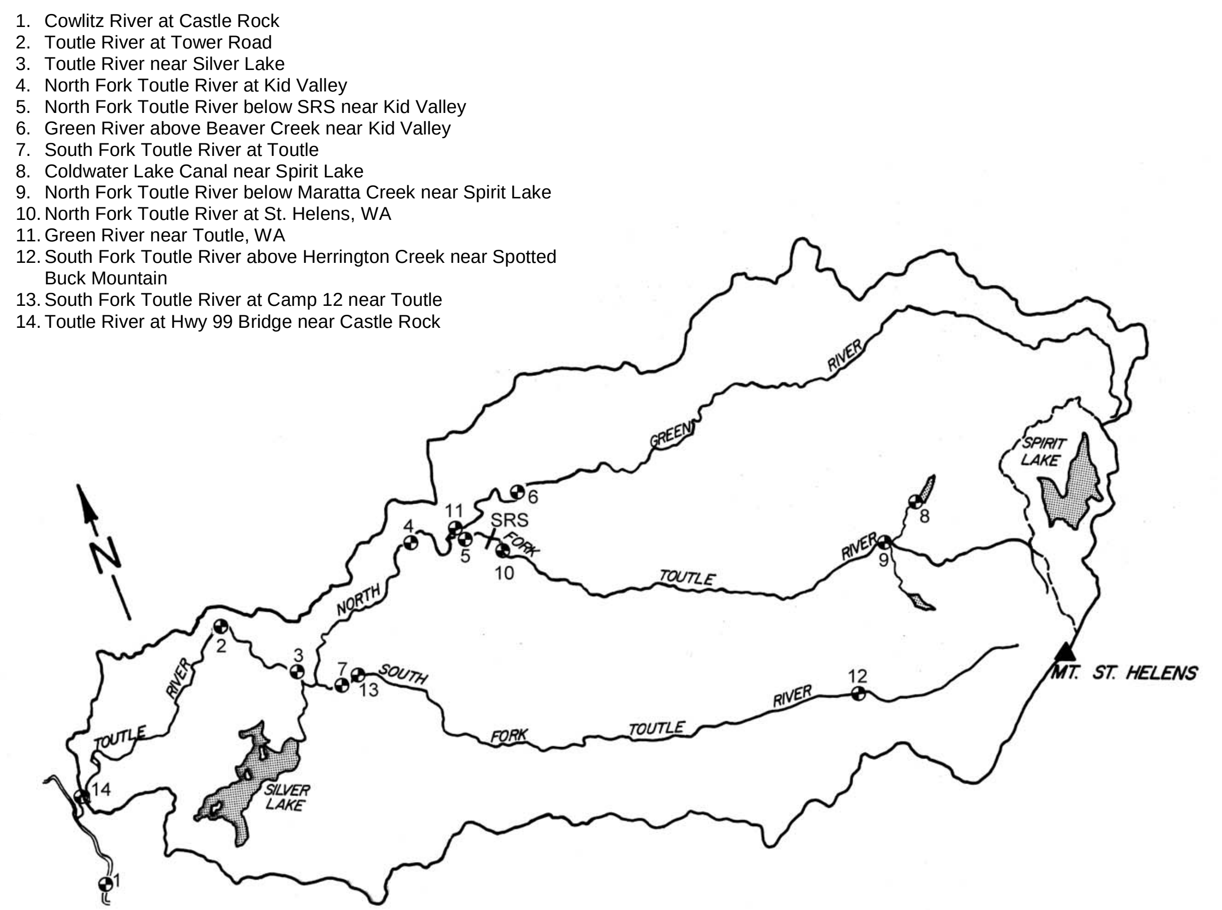

Figure 2.1 Watershed Map with USGS Gage Locations

For a variety of reasons, many of the USGS gages identified offer incomplete records of information. Table 2.1 summarizes the gages located in the Toutle Basin along with the corresponding periods of record.

Table 2.1 USGS Gaging Stations and Periods of Record

Gage Name	USGS Gage No.	Drainage Area (mi^2)	Water Year 1920s	1930s	1940s	1950s	1960s	1970s	1980s	1990s	2000-2007
Coldwater Lake Canal near Spirit Lake	14240352	36.2									
North Fork Toutle River Below Maratta Creek near Spirit Lake	14240370	--									
North Fork Toutle River at St. Helens	14240500	124									
North Fork Toutle River Below SRS near Kid Valley	14240525	175									
Green River above Beaver Creek near Kid Valley	14240800	129									
Green River near Toutle	14241000	131									
North Fork Toutle River at Kid Valley	14241100	284									
South Fork Toutle River above Herrington Creek near Spotted Buck Mtn.	14241465	34.4									
South Fork Toutle River at Camp 12 near Toutle	14241490	117									
South Fork Toutle River at Toutle	14241500	120									
Toutle River near Silver Lake	14242500	474									
Toutle River at Tower Road	14242580	496									
Toutle River at Hwy. 99 Bridge near Castle Rock	14242690	511									
Cowlitz River at Castle Rock	14243000	2238									

Discharge Data, Full Water Year
Discharge Data, Partial Water Year
Suspended Sediment Data, Full Water Year
Suspended Sediment Data, Partial Water Year

USGS gage data having the highest temporal density as well as being located nearest to modeling reaches include:

1) North Fork Toutle River below the SRS near Kid Valley Gage No. 14240525,
2) Toutle River at Tower Road Gage No. 14242580, and
3) Cowlitz River at Castle Rock Gage No. 14243000.

While the USGS gage at Castle Rock contains data dating back to the 1920s, several gaps exist particularly in the summer months. Upstream gages on the Cowlitz River below Mayfield Dam, WA, and on the Toutle River at Tower Road, along with an estimation of local discharges based on drainage area ratios, were used to supplement the missing data in the Castle Rock gage. Additional information can be found in Section 2.4.

Sediment transport modeling along the Toutle and Cowlitz Rivers utilized the USGS information for both calibration and long-term simulation periods. Development of long-term daily discharge data to forecast future years out to 2035 required consideration of non-homogeneity in the historical sediment record associated with the placement of the SRS on the Toutle River. Construction of the SRS along the North Fork of the Toutle River was completed in Dec 1989. For the period from 1989 to 1998, flow through the SRS was directed towards an outlet works of six tiers of five 3-ft diameter pipes. As originally intended, closure of the individual tiers of pipes was based on the accumulation of sediment near the structure. By Apr 22, 1998, all six tiers of pipes were closed and all runoff was diverted directly to the ungated-overflow spillway. As a result, sediment loads prior to 1998 represent a different level of trapping efficiency in the SRS than sediment loads after 1998. To satisfy basic stationarity assumptions, data from the period of 1999 to 2007 were used to develop a surrogate set of data to forecast mean hydrology out to 2035.

2.2 Gage Data

2.2.1 Exceedance Analysis

A review of the available USGS gage records for the Cowlitz and Toutle Rivers was conducted from WYs 1999 through 2007. Figure 2.2 shows this time series of mean daily discharge along with the dates of major storm events within each water year for the three highest temporal density data sets identified above.

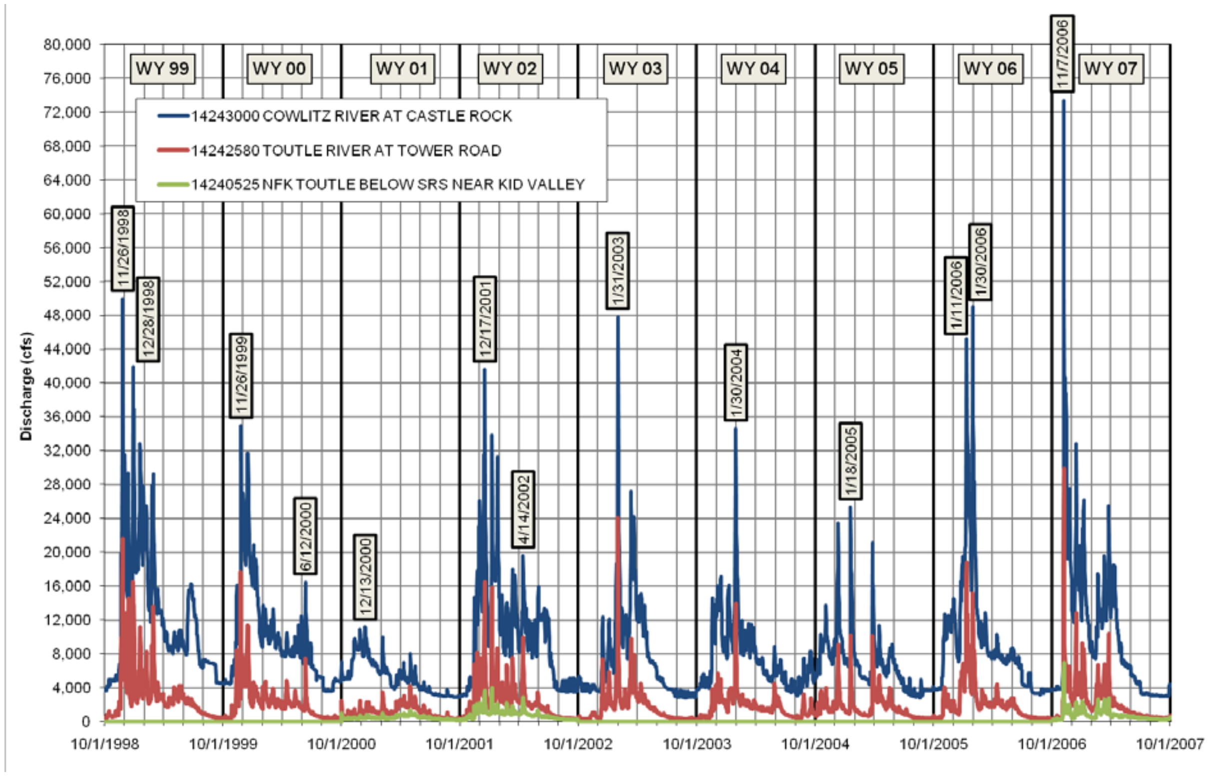

Figure 2.2 Mean Daily Discharge from WYs 1999 to 2007 for the Cowlitz and Toutle Rivers

As illustrated in Figure 2.2, flow rates recorded on the Cowlitz River correlate closely with recorded flow rates on the Toutle River. From the mean daily data presented in Figure 2.2, it clear that the Nov 2006 event stands out as the largest event in the selected time period with a mean daily maximum of 73,300 cubic feet per second (cfs) on the Cowlitz and 29,900 cfs on the Toutle. Annual mean daily peak discharges were extracted for both the Cowlitz River at Castle Rock and the Toutle River at Tower Road for the period of records. The exceedance probability corresponding to the mean daily peak discharges were then determined using the Annual Frequency curves that were developed for the hydrologic analysis in the 2009 Level of Protection study (USACE 2009b) performed along the Cowlitz River. These peak discharges along with the respective exceedance probabilities are summarized in Table 2.2 for the period from 1999 to 2007.

Table 2.2 Annual Peak Discharges from 1999 to 2007

Cowlitz River				
Water Year	Annual Peak Flow Rate (cfs)	Date	Exceedance Probability	Recurrence Interval
1999	57,600	11/26/1998	0.3	3.4
2000	41,700	11/25/1999	0.59	1.7
2001	11,600	11/27/2000	0.99	1
2002	51,400	12/17/2001	0.39	2.5
2003	69,000	1/31/2003	0.17	5.8
2004	38,100	1/30/2004	0.66	1.5
2005	29,600	1/18/2005	0.83	1.2
2006	56,200	1/30/2006	0.31	3.2
2007	77,300	11/7/2006	0.11	8.7
Toutle River				
Water Year	Annual Peak Flow Rate (cfs)	Date	Exceedance Probability	Recurrence Interval
1999	27,800	11/26/1998	0.16	6.2
2000	23,900	11/25/1999	0.26	3.9
2001	4,660	4/30/2001	1.13	0.9
2002	23,300	12/17/2001	0.27	3.7
2003	32,200	1/31/2003	0.98	10.3
2004	17,000	1/30/2004	0.53	1.9
2005	12,200	1/18/2005	0.82	1.2
2006	22,200	1/11/2006	0.31	3.2
2007	37,200	11/7/2006	0.05	19.3

From Table 2.2, the storm event in Nov 2006, WY 2007, represents an exceedance probability of approximately 0.11 or nearly a 9-year event at Castle Rock and 0.05 or nearly a 20-year event at Tower Road. At Tower Road, the Nov 2006 event that produced 37,200 cfs was exceeded three times (Feb 1996, Feb 1982, and Dec 1982) for the period of record dating back to Mar 1981. On the Cowlitz River, the maximum measured flow rate on Nov 2006 of 77,300 cfs was exceeded seven times (Feb 1996, May 1980, Jan 1990, Dec 1975, Dec 1977, Jan 1972, and Nov 1986) in the post-regulation period of record (beginning in 1969) at the Castle Rock gage. For the 9 years following 1999, the average peak discharge was computed to be 48,056 on the Cowlitz at Castle Rock and 22,273 on the Toutle River at Tower Road. These average peak discharges represent an exceedance of approximately 0.50 (2-year event) on the Cowlitz River at Castle Rock and 0.30 (3-year event) for the Toutle River at Tower Road. Table 2.3 shows the annual peak discharges ranked in order of greatest to smallest at both Castle Rock and at Tower Road.

Table 2.3 Ranked Annual Peak Discharges from 1999 to 2007

Cowlitz River at Castle Rock			Toutle River at Tower Road		
Water Year	**Date**	**Peak Discharge (cfs)**	**Water Year**	**Date**	**Peak Discharge (cfs)**
2007	11/7/2006	77,300	2007	11/7/2006	37200
2003	1/31/2003	69,000	2003	1/31/2003	32200
1999	11/26/1998	57,600	1999	11/26/1998	27800
2006	1/30/2006	56,200	2000	11/25/1999	23900
2002	12/17/2001	51,400	2002	12/17/2001	23300
2000	11/25/1999	41,700	2006	1/11/2006	22200
2004	1/30/2004	38,100	2004	1/30/2004	17000
2005	1/18/2005	29,600	2005	1/18/2005	12200
2001	11/27/2000	11,600	2001	4/30/2001	4660

2.2.1 Volume Analysis

While WY 1999 is ranked below WY 2007 in terms of peak discharge, the nature of the Nov 1998 storm event produced a volume of water that was larger than the 2006 event. By integrating the daily discharge record, a measurement of total annual volume was computed and compared for each water year. Figure 2.3 shows the Total Annual Discharge for the Cowlitz River at Castle Rock and Figure 2.4 shows the Total Annual Discharge for the Toutle River at Tower Road.

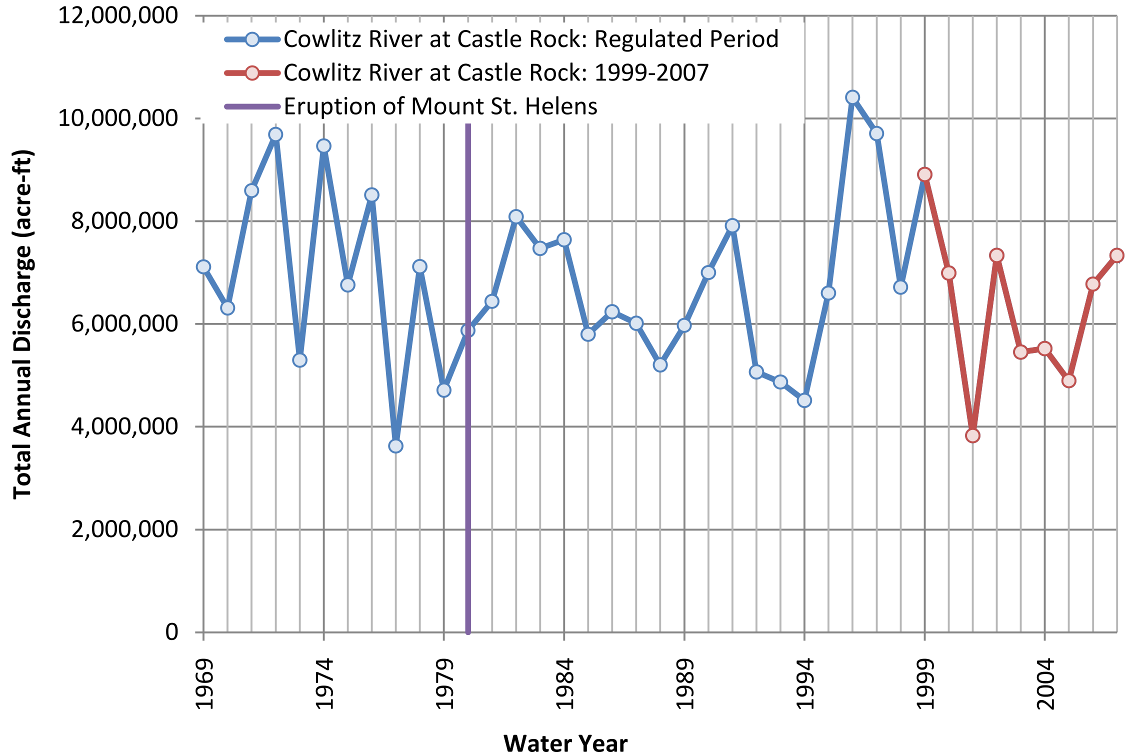

Figure 2.3 Total Annual Discharge on the Cowlitz River at Castle Rock

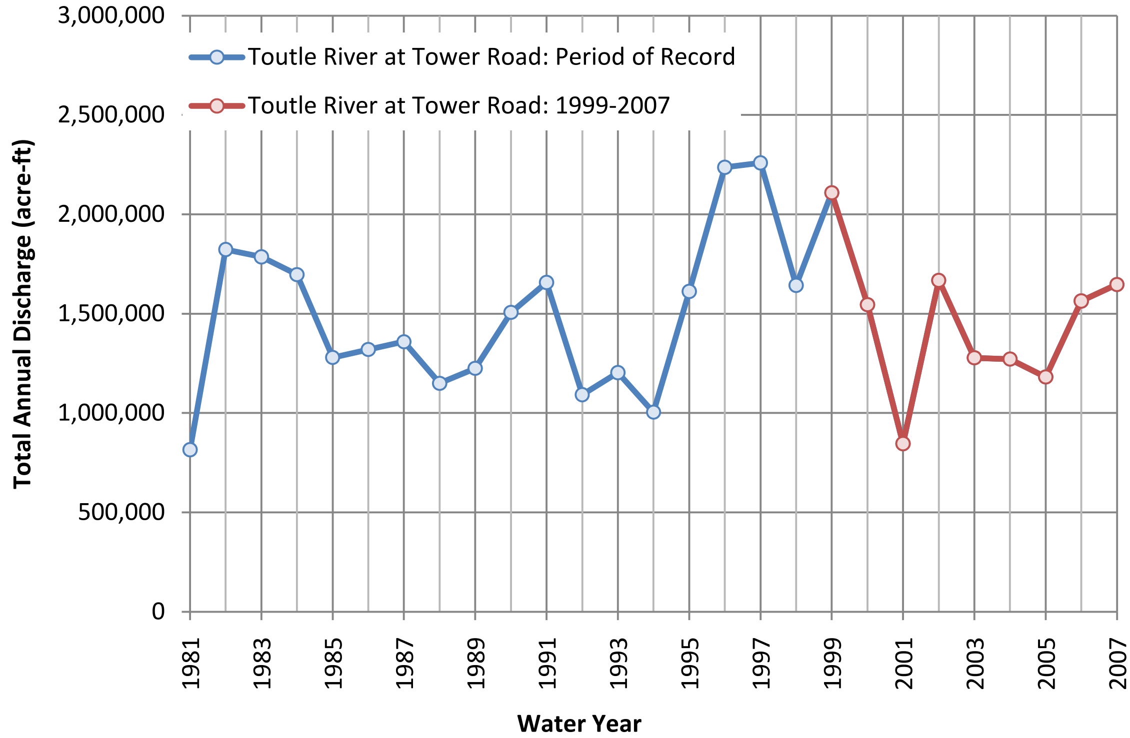

Figure 2.4 Total Annual Discharge on the Toutle River at Tower Road

Figure 2.3 and Figure 2.4 both show that the years from 1999 to 2007 represent reasonably average years when compared to the entire period of record. For Castle Rock the average annual volume from 1999 to 2007 is 6,337,295 acre-ft compared to 6,711,367 acre-ft for the regulated period of record. On the Toutle River at Tower Road, the average annual discharge is 1,456,622 compared to 1,472,009 for the period of record. Figure 2.3 and Figure 2.4 also show that for the period from 1999 to 2007 the total annual discharge fluctuates within a band from 8,909,664 to 3,828,061 acre-ft at Castle Rock and 2,108,338 to 846,333 acre-ft on the Toutle River at Tower Road. These ranges compare well with the measured values from the respective periods of record.

In addition to evaluating the Total Annual Discharge at Castle Rock and at Tower Road, two other gages that were not affected by the eruption of MSH were used to evaluate how representative the period from 1999 to 2007 is to the overall period of record. Both additional gages are within the vicinity of the modeled reach and have a relatively homogeneous data set. The annual discharge volume was computed from the mean daily data obtained from the USGS on the Cowlitz River at Kosmos, WA (USGS 14233500), and on the East Fork of the Lewis River near Heisson, WA. Figure 2.5 and Figure 2.6 show plots of the Annual Discharge Volume in acre-ft for these two gages.

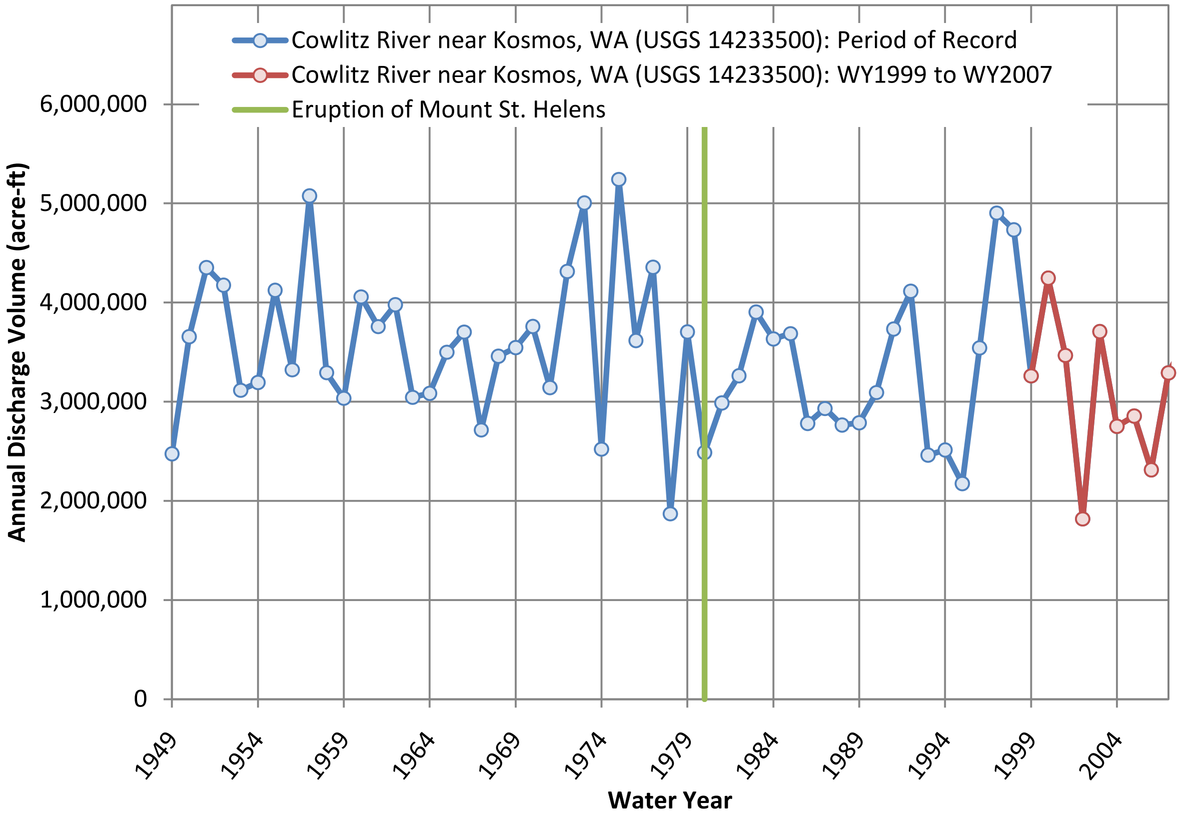

Figure 2.5 Total Annual Discharge on the Cowlitz River near Kosmos, WA

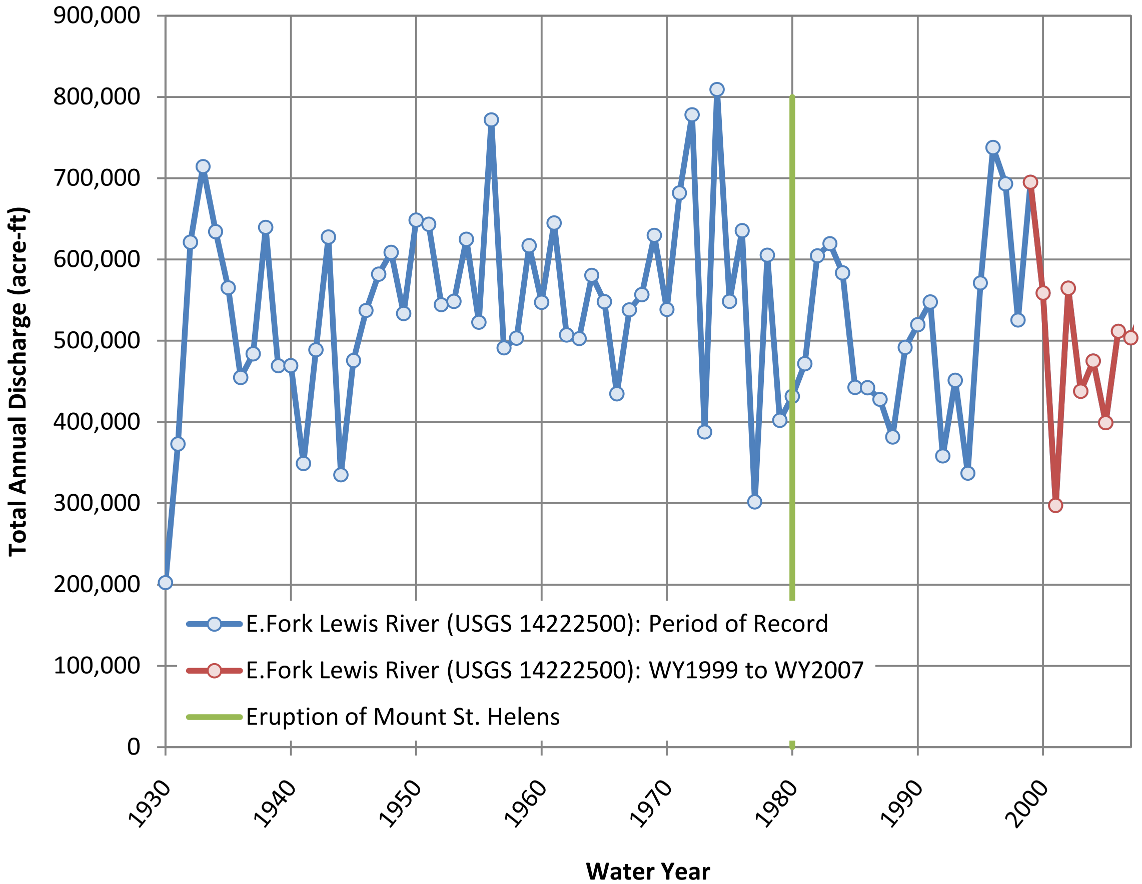

Figure 2.6 Total Annual Discharge on the East Fork of the Lewis River

Both Figure 2.5 and Figure 2.6 show that the total annual discharge for the period from 1999 to 2007 compares well with the total period of record. Table 2.4 compares the computed average annual discharge from 1999 to 2007 for the four USGS gage sites to the total annual discharge for the respective period of record. In all cases, the discharge from 1999 to 2007 is within 10% of the computed annual discharge for the entire period of record.

Table 2.4 Average Total Annual Discharge Values

Location	USGS Gage	Average Total Annual Discharge (acre-ft) 1999 to 2007	Period of Record	Difference
Cowlitz River at Castle Rock	14243000	6,337,295	6,711,367	5.6%
Toutle River at Tower Road	14242580	1,456,622	1,472,009	1.0%
Cowlitz River near Kosmos, WA	14233500	3,078,746	3,418,622	9.9%
E. Fork Lewis Near Heisson, WA	14222500	493,708	528,467	6.6%

2.2.2 Frequency Analysis

A review of mean daily discharges was conducted to determine if the frequency of discharges measured during the 9 years matched to data historically experienced. Daily average flow rate values from four USGS gages were binned into ten categories with a corresponding frequency. Binning of the daily average flow rates was performed for both the period of record and the 9-year period used for future forecasting. The USGS gages used for this analysis are: Cowlitz River at Castle Rock (USGS 14243000), Toutle at Tower Road (USGS 14242580), Cowlitz River at Kosmos, WA (USGS 14233500), and the East Fork of the Lewis River near Heisson, WA (USGS 14222500). The two additional gages, one at the Cowlitz River at Kosmos, WA, and the other on the East Fork of the Lewis River, were chosen because they are within close proximity to the modeling reach and the gage record for both sites are relatively homogeneous. Figure 2.7 shows the histograms resulting from the frequency analysis for the four gages mentioned above.

The frequency distributions presented in Figure 2.7 show that the 9-year period from 1999 to 2007 are distributed in a very similar manner as the historic data set. This analysis further indicates that in addition to similar large events, the 9-year period from 1999 to 2007 also contains a reasonable characterization of moderate to low discharges as well. This is important because the moderate events have the capability to mobilize a substantial amount of sediment.

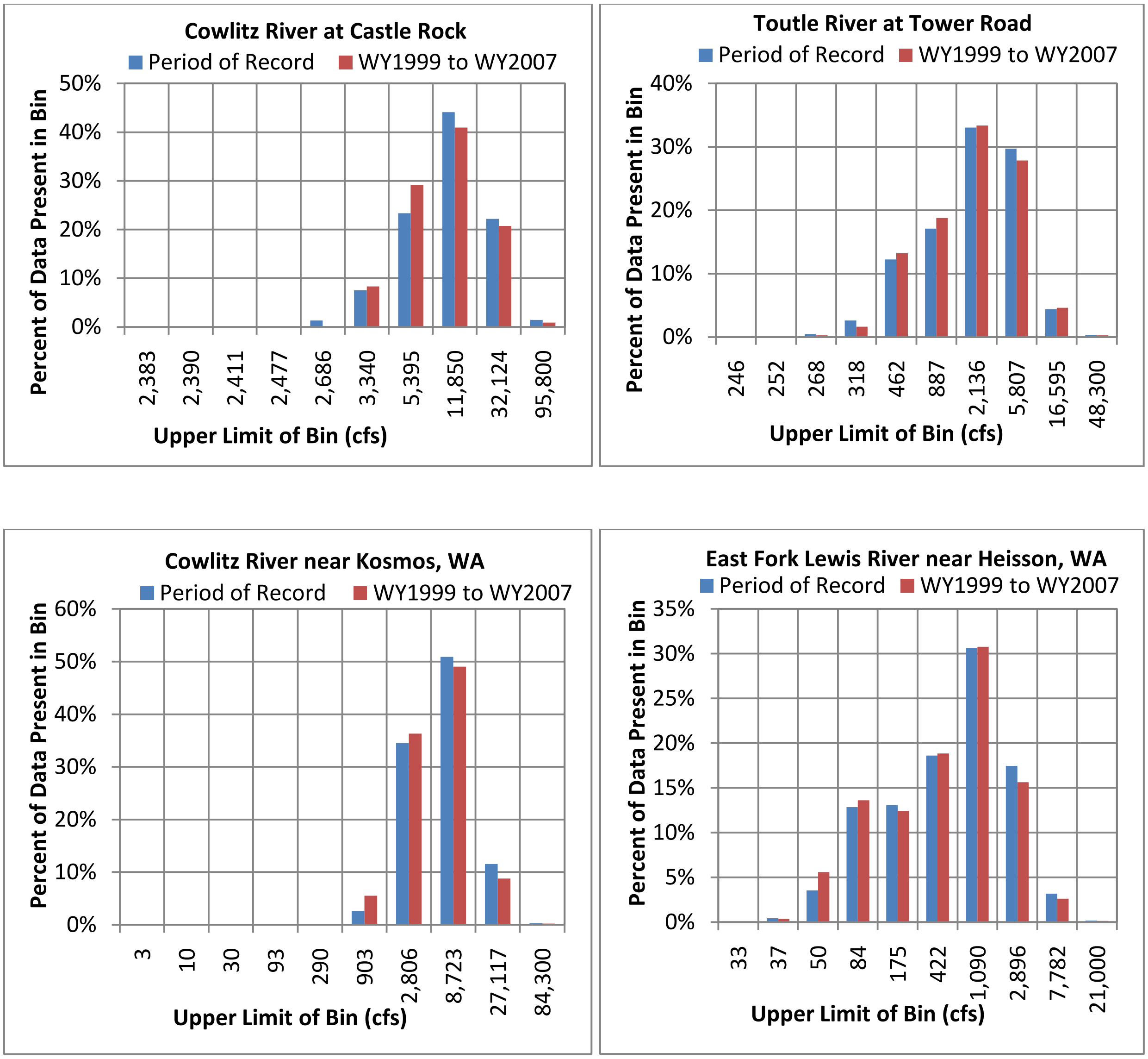

Figure 2.7 Frequency Histograms for Four USGS Gages within the Cowlitz-Toutle Basin

2.2.3 Conclusion

Forecasting hydrology patterns for future years from 2007 to 2035 require the basic assumption that the data used for forecasting are representative of the entire period of record. Within the Cowlitz-Toutle Basin, the robust data sets on the Cowlitz at Castle Rock and the Toutle at Tower Road were used to compare the hydrologic patterns in the years 1999 to 2007 to the period of record. A threefold approach was used to evaluate the representativeness of these years: 1) the peak discharges in the latter years were compared to the duration frequency curves developed based on all available data, 2) the annual discharge in acre-ft was computed to compare the annual volume of water for the 9-year period to the annual volume for the period of record, and 3) the daily average discharge for the period from 1999 to 2007 was compared to

the period of record using a binned frequency analysis. The result of these three analyses reveal that the 9-year period from 1999 to 2007 contains some years of significant rainfall events and other years with very low amounts of rainfall but the range of hydrologic data measured during this period is within the historical range of measured data. Justification for the use of the 9-year period to adequately represent future conditions out to 2035 with a stationarity assumption for the period of record is therefore established. Considerations of global climate change are not addressed in this analysis due to the relatively near 2035 end-of-project authorization.

2.3 North Fork Toutle River Hydrology

Daily average discharge data at the North Fork gage below the SRS were available for the time periods of 2/2/96 through 9/30/98, 10/1/00 through 10/1/02, and 10/1/06 through 3/3/08. A relationship between North Fork gage data and Tower Road was developed to supplement missing daily discharge data on the North Fork below the SRS. The Toutle River at Tower Road gage has the most comprehensive data set in the watershed, with daily average discharge data available for all years of interest between 1999 and 2007. The relationship between North Fork below the SRS and Tower Road gage data is shown graphically in Figure 2.8. Daily average discharges for WYs 1999 through 2007 are shown in Figure 2.9.

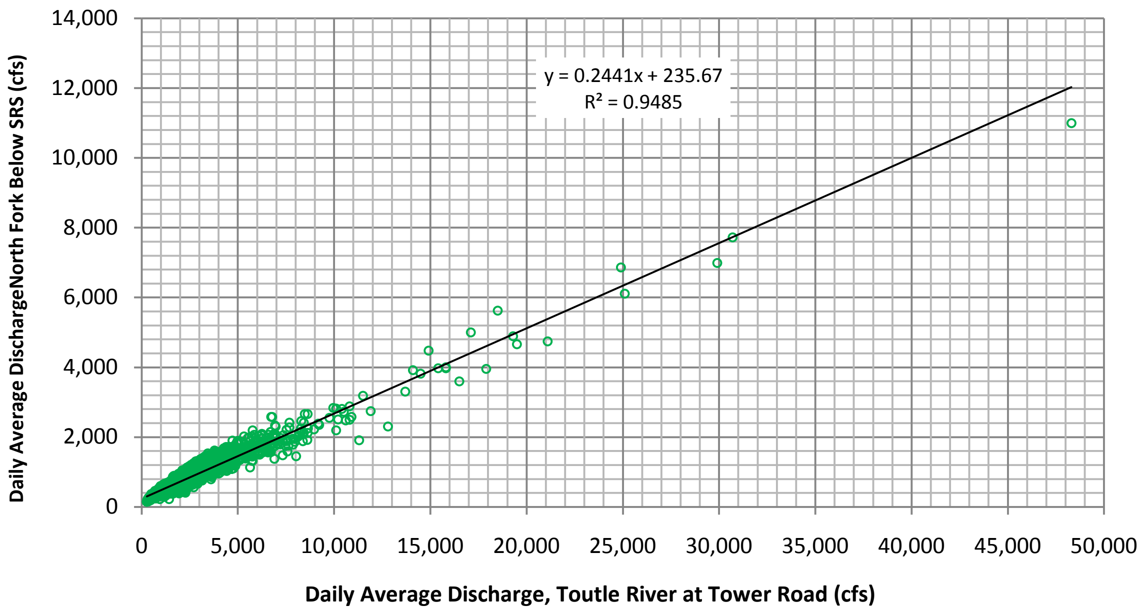

Figure 2.8 North Fork Toutle River below the SRS Daily Average Discharge Rating Curve Using Relationship to Toutle River at Tower Road

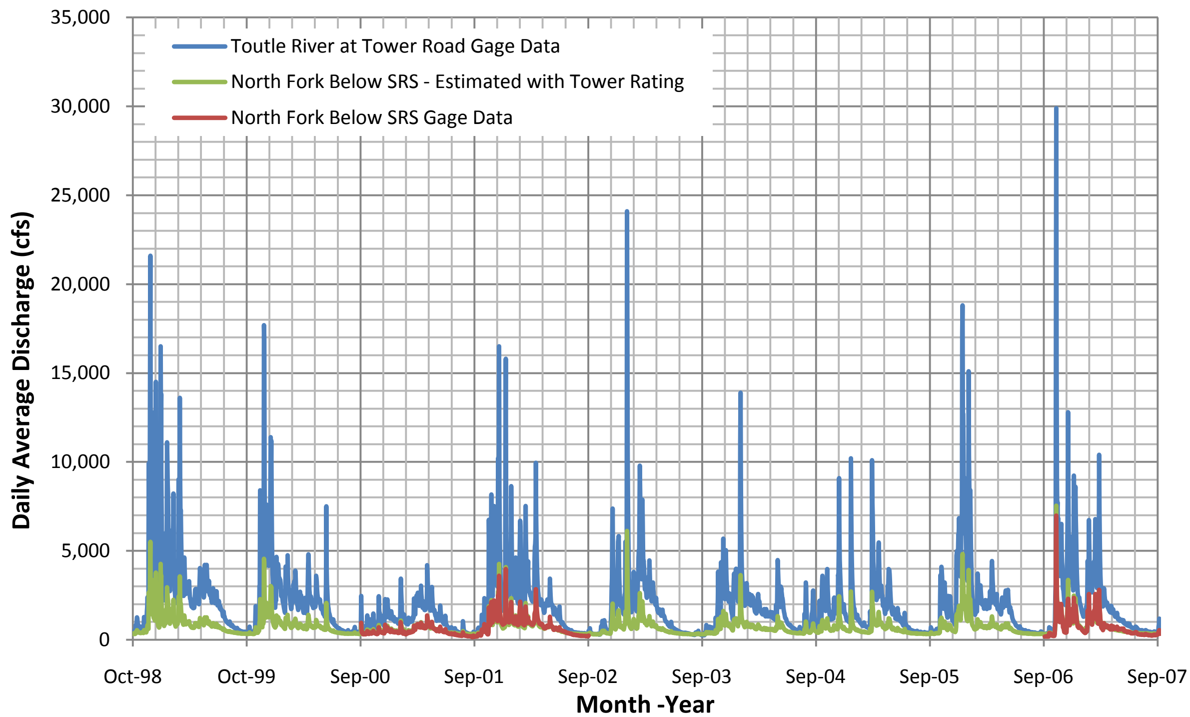

Figure 2.9 Daily Average Discharge Time Series for Toutle River at Tower Road Gage, North Fork below the SRS Gage, and North Fork below the SRS Rating Curve

There are several tributaries that feed flow into the North Fork Toutle River above the SRS. Four major tributaries were identified including Hoffstadt Creek, Deer Creek, Alder Creek, and Pullen Creek. Daily average flow from these four tributaries is required for modeling of the area upstream of the SRS. The total daily average discharge data at the gage below the SRS were pro-rated by contributing drainage area to generate a daily average flow data set for each tributary, see Table 2.5 and Figure 2.10.

Table 2.5 Percentage of Tributary Area

Tributary	% of Contributing Area
North Fork at Elk Rock/N1 (Upstream)	56.2
Hoffstadt Creek (N1 + N2)	22.2
Deer Creek (S1)	6.8
Alder Creek (S2)	10.6
Pullen Creek (N3 + N4)	4.2

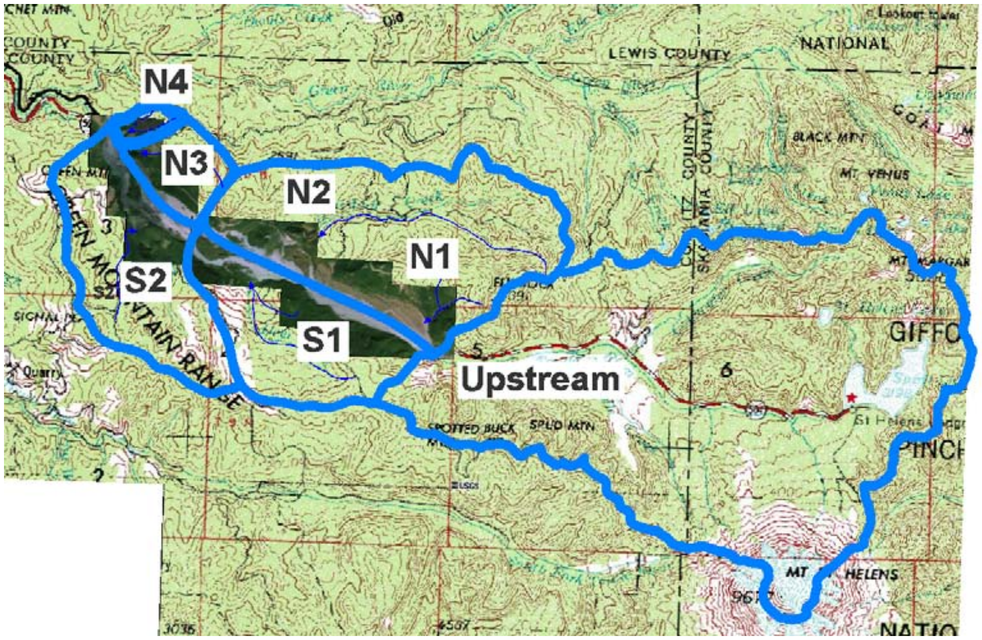

Figure 2.10 Distribution of Contributing Drainage Area

The pro-rated discharge for the North Fork of the Toutle River above the SRS was used to facilitate the 1-D and 2-D modeling efforts within the sediment plain.

2.4 Cowlitz River Hydrology

The hydrology used to support the mobile-bed modeling effort for the lower 20 miles of the Cowlitz River consists of the data available at the Castle Rock gage as well as estimates of local contributions from adjacent tributaries. The Cowlitz River is gaged at Castle Rock about 18 miles upstream of the confluence with the Columbia (USGS 14243000). For the present model study, the Coweeman River that drains into the Cowlitz just above the confluence with the Columbia is added to the flow from Castle Rock, to account for more than half of the previously unaccounted-for drainage area in the Cowlitz basin.   The minor creeks between Castle Rock and Coweeman are ignored due to their relatively small flow contribution and to simplify modeling in the HEC-RAS mobile-bed model.

The daily flow data set from the Cowlitz at Castle Rock gage (USGS 14243000) has several gaps, particularly in the summer months, so an effort was made to find alternative data sources and generate synthetic flow data to supplement the gage data (Figure 2.11). Sub-daily flow data were found on the USACE's Dataquery website (http://www.nwd-wc.usace.army.mil/perl/dataquery.pl), and daily flow data were gathered from the two upstream gages, Cowlitz River below Mayfield Dam, WA (USGS 14238000), and Toutle River at Tower Road near Silver Lake, WA (USGS 14242580). The quality of the sub-daily data from

Dataquery was questionable, due to several obviously erroneous points and a general disagreement with the verified USGS daily data.

USGS gages upstream of Castle Rock were used to estimate flow at Castle Rock. The Cowlitz below Mayfield Dam or "Upper Cowlitz" data were combined with Toutle River flow adjusted to account for the additional drainage area below the two gages. The Toutle River flow was used to estimate the locals because it was not regulated upstream, as opposed to the Upper Cowlitz. There was a strong correlation for low flows (less than 20,000 cfs) with the following relationship:

$$\text{Castle Rock} = \text{Upper Cowlitz} + [\text{Toutle at Tower Road} * ((1 + DA_{locals}/DA_{Toutle})^{0.6})]$$

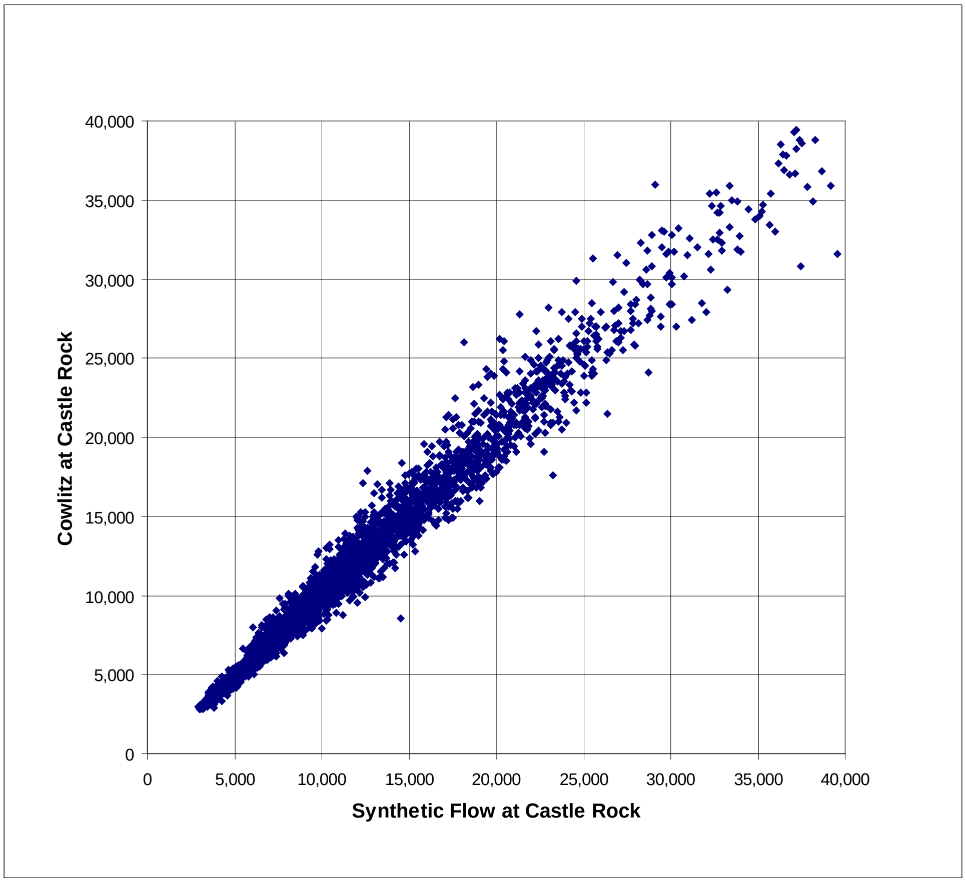

Figure 2.11 Actual Average Daily Flow Data from Castle Rock vs. the Synthetic Flow Data Based on Upstream Gages Using the above Relationship

Since almost all of the data gaps are during low-flow periods after the flood season and freshet, the use of the above relationship to generate synthetic data is suitable. These synthetic data were used to supplement the USGS daily data to complete the period of record for this study.

2.4.1 Coweeman River

The Coweeman River is not currently gaged, however, the "Coweeman River near Kelso, WA" gage (USGS 14245000) collected flow data from 1950 to 1982. In attempting to find adequate relationships for the Coweeman basin, nearby gages with no upstream storage component were selected. The observed data on the Coweeman were compared to the following gages: South Fork Toutle near Toutle (USGS 14241500), Toutle River at Silver Lake (USGS 14242580), and East Fork Lewis River near Heisson, WA (USGS 14222500). All three basins represent hydrologic-similar conditions. The Coweeman, located approximately 30 miles from the Coweeman River's confluence with the Cowlitz, had the highest correlation with the East Fork of the Lewis River. Synthetic Coweeman flows are calculated using the relationship for the East Fork Lewis River in the scatter plot presented in Figure 2.12, and adjusted using the drainage area method.

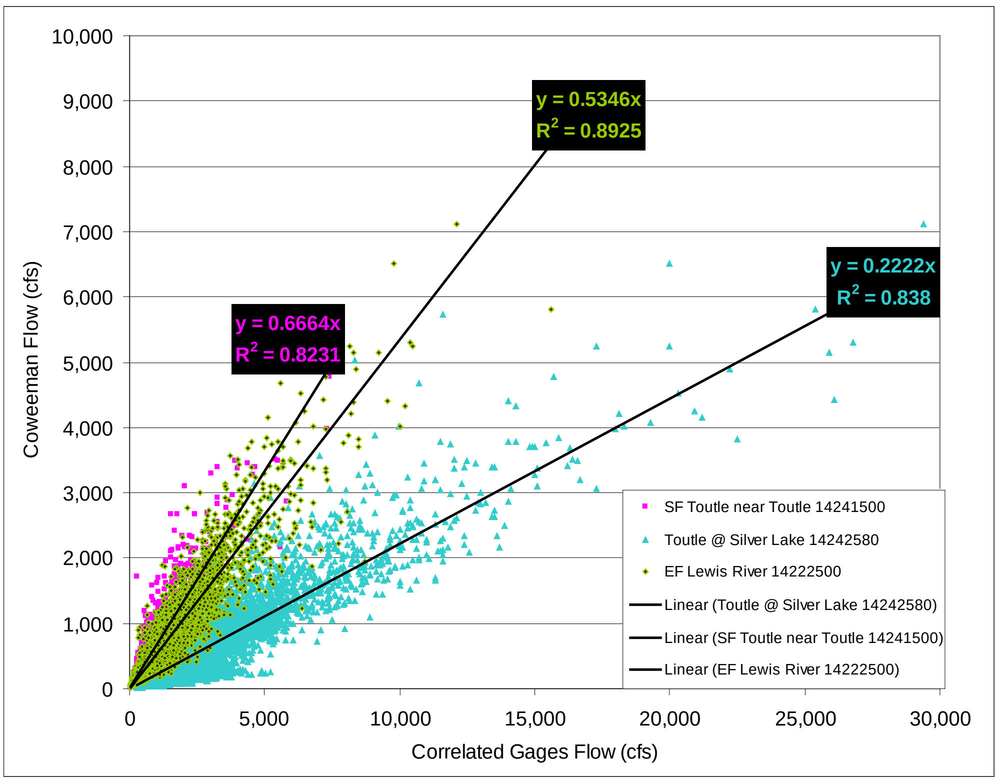

Figure 2.12 Average Daily Flow Data from the Old Coweeman Gage Correlated with Nearby Gages

The estimated Coweeman flows, data at Castle Rock, and the estimate of flows upstream of Castle Rock were compiled into one file for use in the modeling efforts along the Cowlitz River.

2.5 Forecasting Sequence

A 28-year series of water and sediment discharges was developed for use in the long-term forecast modeling based on 9 years of historic hydrologic record (WYs 1999 to 2007). Data developed in the Sediment Budget for WYs 1999 to 2007 were used as surrogates for future forecast years through 2035. A Monte-Carlo bootstrapping method was utilized to forecast the total sediment load delivered to the mouth of the Toutle River by 2035. The bootstrapping method provides a range of possible forecast estimates by generating 10,000 combinations of the nine surrogate years in random 28-year sequences. Each of the 10,000 sequences is then assigned a percent exceedance value based on the cumulative sediment load at the mouth of the Toutle River calculated in 2035.

The sequence producing the 50% exceedance value of the cumulative sediment load at the mouth of the Toutle River in 2035 was initially selected and reported in the Sediment Budget for use in the forecast modeling, shown as Sequence A in Table 2.6. The occurrence of each hydrologic year in Sequence A is shown as blue bars in Figure 2.13. Subsequent review of Sequence A was conducted to ensure that it was representative of the average range of hydrologic and sediment input combinations. It should be noted that the 9 years of hydrologic and sediment metrics do not always have corresponding trends.

Table 2.6 Forecast Sequence through 2035 Using Surrogate Years 1999 to 2007

Forecast Year	Surrogate Year	
	Sequence A	Sequence B
	50% Exceedance of Load at Mouth of Toutle River	Sequence Selected for Forecast Modeling
2008	1999	2003
2009	2000	2006
2010	2005	2005
2011	2007	2004
2012	2003	2006
2013	2004	2004
2014	2001	2003
2015	2006	2007
2016	2002	2002
2017	1999	2003
2018	2002	2001
2019	2004	2006
2020	2006	2003
2021	1999	1999
2022	2002	2004
2023	1999	2005
2024	2000	2000
2025	1999	2006
2026	2007	2002
2027	2000	2006
2028	2004	2002
2029	2002	2001
2030	2000	2007
2031	1999	2002
2032	2003	2003
2033	2004	2005
2034	2002	2002
2035	2006	2000

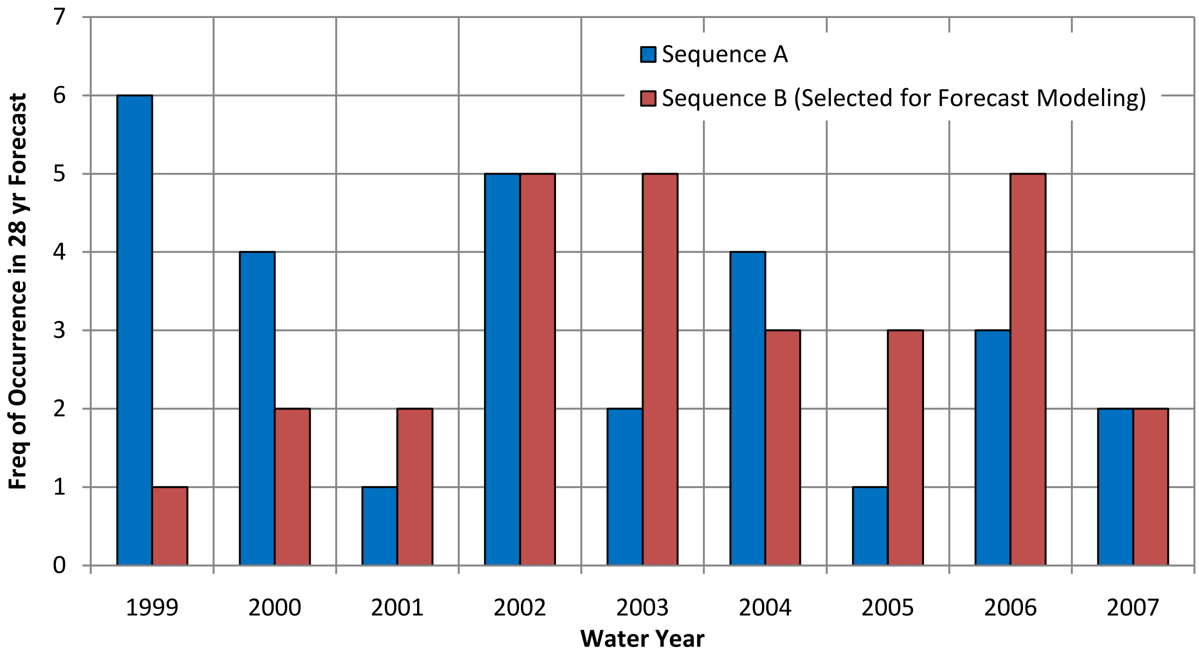

Figure 2.13 Frequency of Occurrence of Surrogate Water Years in Long-term Forecasting

The bootstrapping method of forecasting was also conducted on three additional hydrologic and sediment metrics including: 1) North Fork Toutle River water discharge by volume, 2) debris avalanche erosion, and 3) estimated sediment output from the SRS. The values of each metric used in the bootstrapping analysis for WYs 1999 to 2007 is provided in Table 2.7. The bootstrapping trajectories for each of the three metrics, plus the original bootstrapping of sediment load at the mouth of the Toutle River are shown in Figure 2.14 through Figure 2.17.

Table 2.7 Annual Values of Hydrologic and Sediment Metrics for Surrogate Years 1999 to 2007

Water Year	North Fork Annual Discharge Volume [A] (acre-ft)	Debris Avalanche Erosion [B] (M Tons)	Sediment Output from the SRS [C] (M Tons)	Sediment Load at Mouth of Toutle River [C] (M Tons)
1999	684,663	11.4	2.8	4.88
2000	548,240	0.9	3.8	4.55
2001	337,396	0.4	0.5	0.635
2002	603,172	10.5	5.9	7.44
2003	482,264	8.1	4.6	5.27
2004	481,856	3.0	2.1	2.56
2005	459,009	4.4	2.4	2.83
2006	552,114	6.7	4.7	5.29
2007	545,884	26.2	17.4	22.7

[A] Computed using USGS Gage data below the SRS, see Section 2.1.
[B] Debris avalanche erosion estimated using LiDAR data above N1 (from the 2010 SBR).
[C] Sediment budget estimate (from the 2010 SBR).

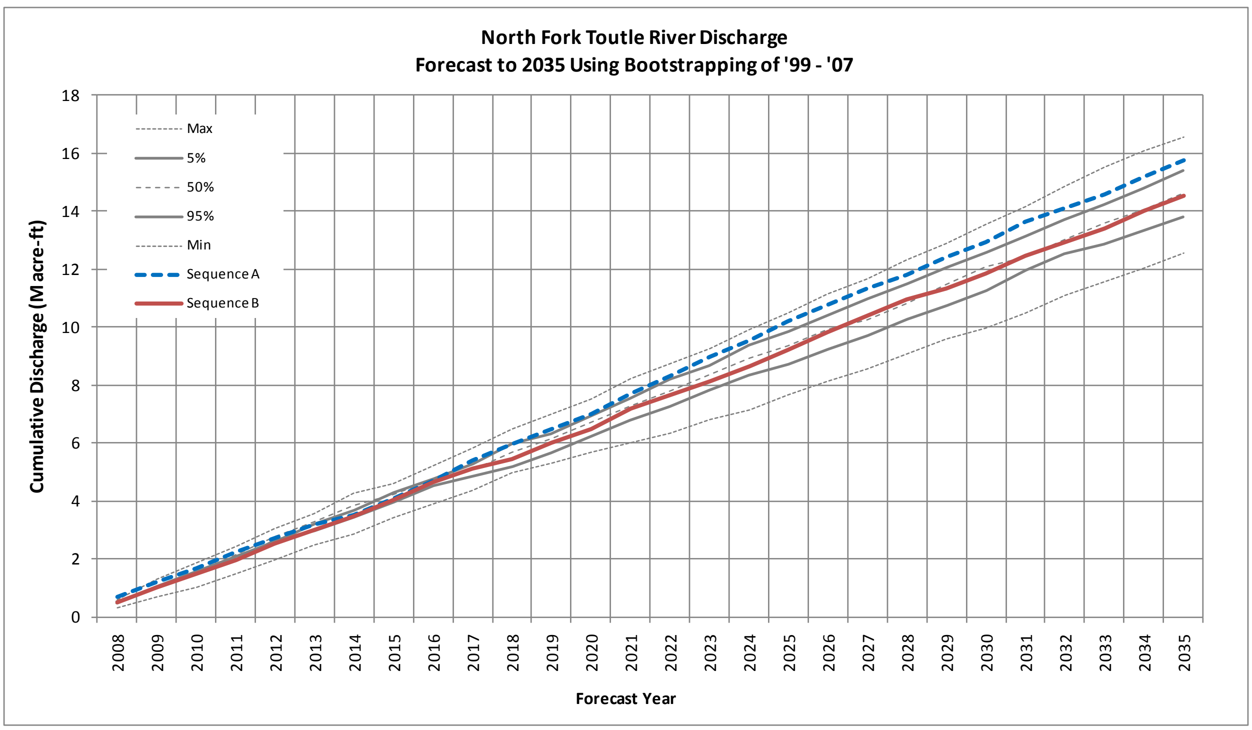

Figure 2.14 Forecast of Cumulative North Fork Toutle River Annual Discharge for Range of 10,000 Bootstrapping Sequences, and Sequence A and Sequence B

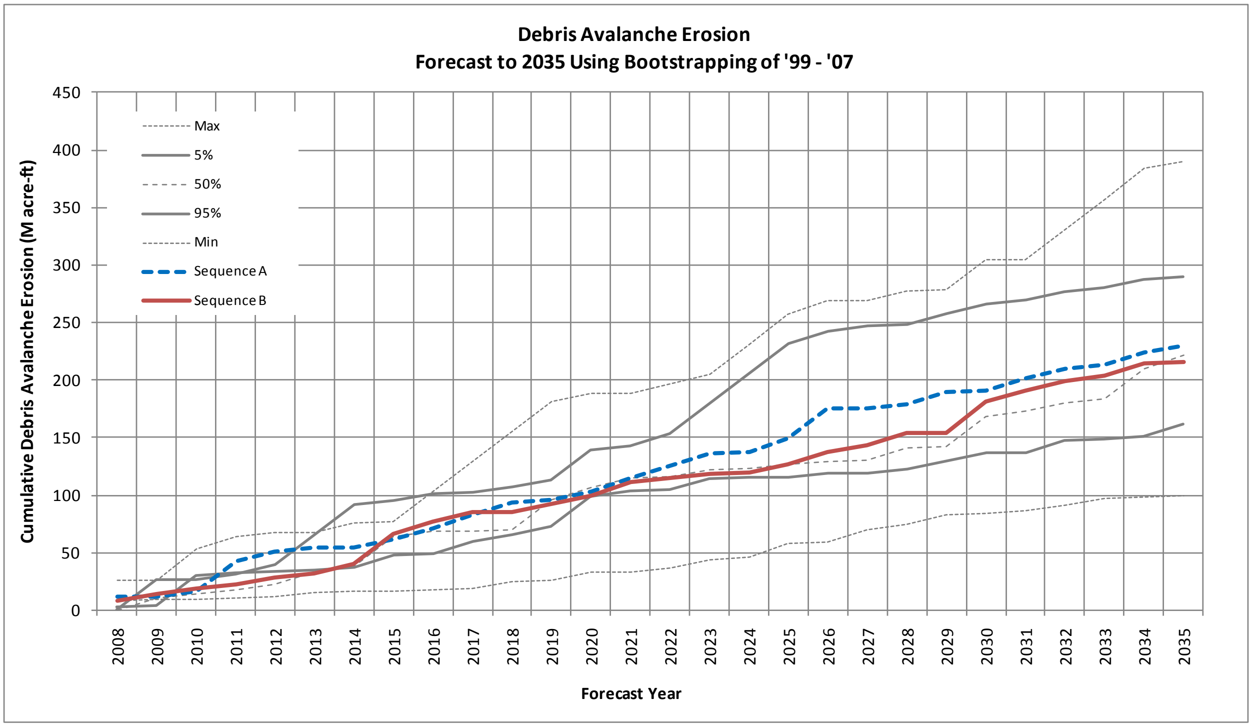

Figure 2.15 Forecast of Cumulative Debris Avalanche Erosion for Range of 10,000 Bootstrapping Sequences, and Sequence A and Sequence B

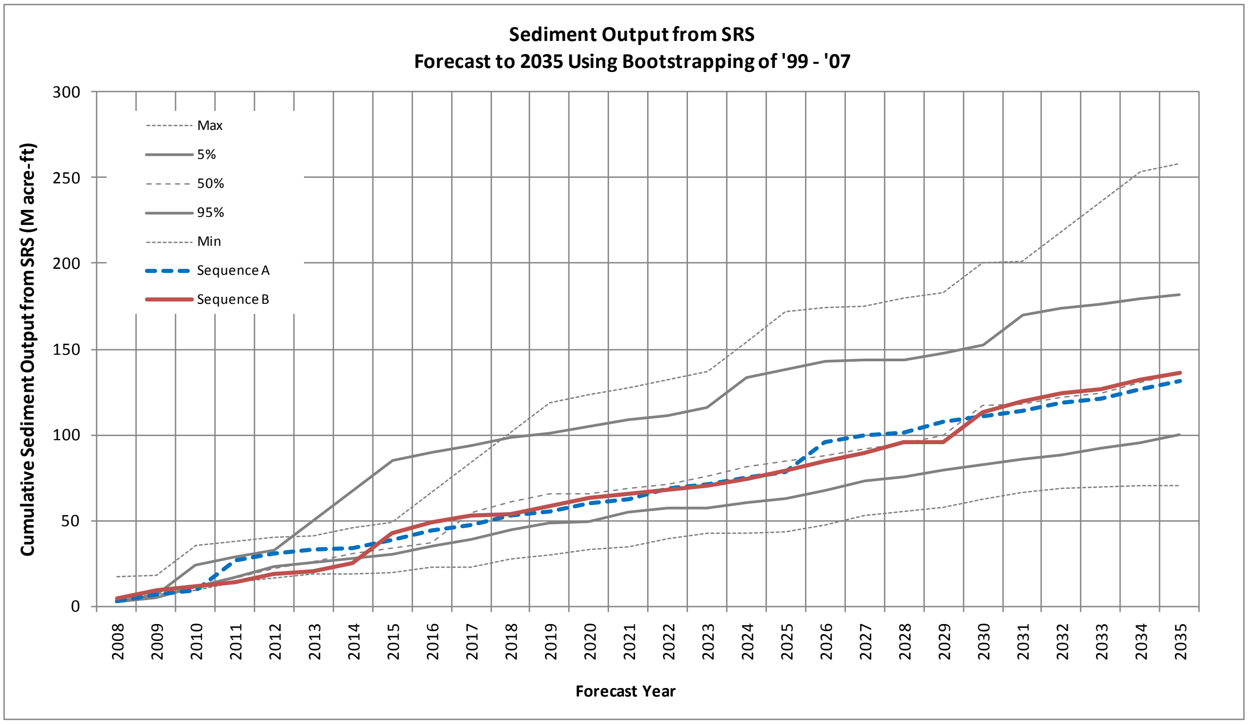

Figure 2.16 Forecast of Cumulative Sediment Output from the SRS for Range of 10,000 Bootstrapping Sequences, and Sequence A and Sequence B

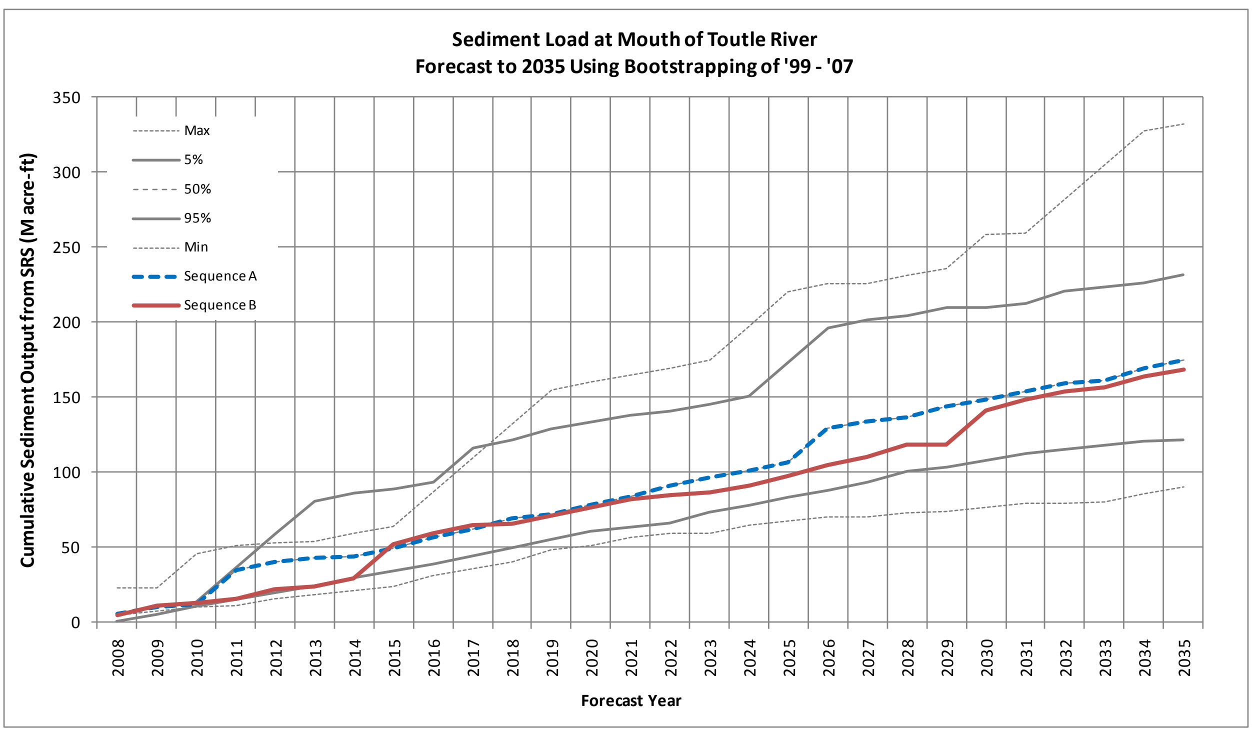

Figure 2.17 Forecast of Cumulative Sediment Load at Mouth of Toutle River for Range of 10,000 Bootstrapping Sequences, and Sequence A and Sequence B

The cumulative value in 2035 of each metric and the corresponding % exceedance were computed using Sequence A. Results of the forecasting analysis of Sequence A show that the North Fork Toutle River discharge has a 1% exceedance value and is greater than the 95% confidence limit. The exceedance values for debris avalanche erosion and sediment output from the SRS for Sequence A were found to be 41 and 58%, respectively. The exceedance values for each of the four metrics are shown graphically in Figure 2.18 and in tabular form in Table 2.8. Review of Sequence A indicates that although it does represent an average forecast of the sediment metrics it does not represent an average hydrologic sequence, and therefore it is not ideal for mean condition forecast modeling.

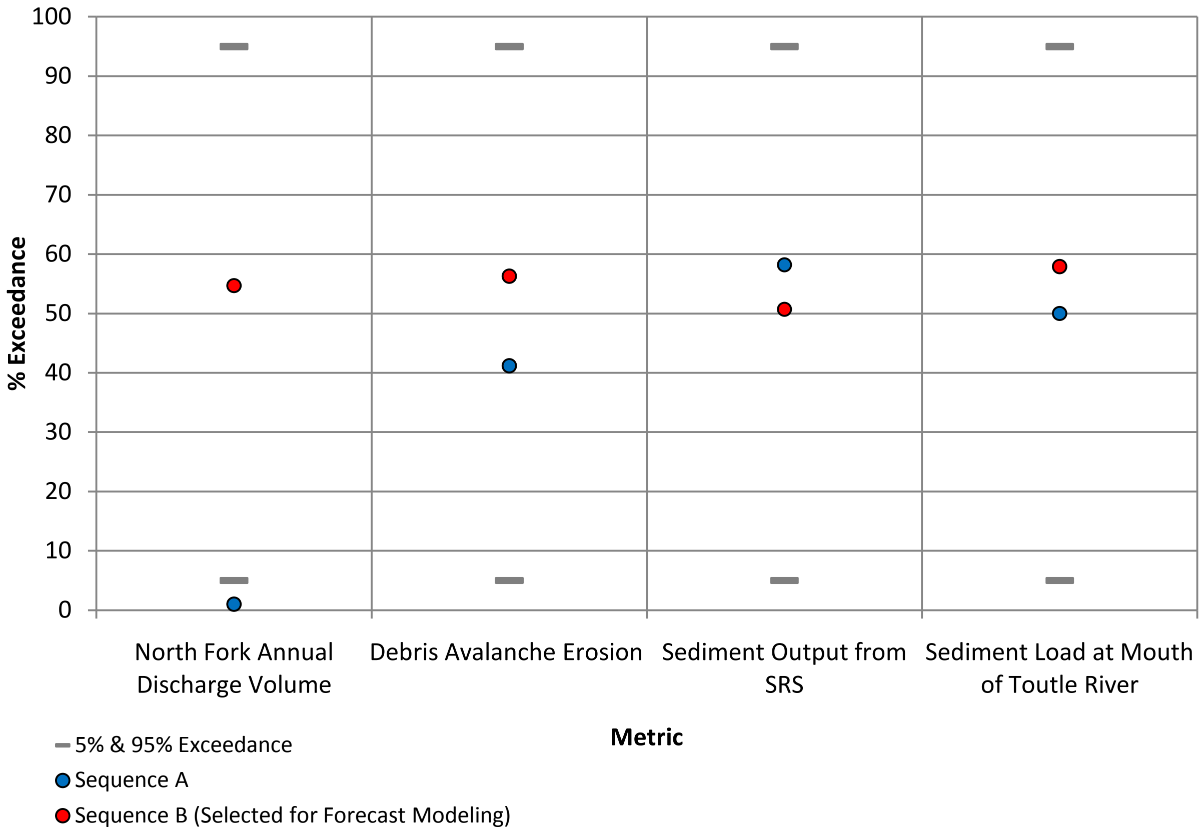

Figure 2.18 Comparison of Exceedance Values of Hydrologic and Sediment Metrics for Original and Selected Modeling Long-term Sequence

Table 2.8 Bootstrapping Results of Hydrologic and Sediment Metrics

	Range of Values in 2035				Value in 2035 Sequence		% Exceedance Sequence	
	Minimum	5%	95%	Maximum	A	B	A	B
North Fork Annual Discharge (M acre-ft)	12.5	13.8	15.4	16.6	15.7	14.6	1%	55%
Debris Avalanche Erosion (M Tons)	99	162	290	390	230	215	41%	56%
Sediment Output from the SRS (M Tons)	71	100	182	258	131	136	58%	51%
Sediment Load at Mouth of Toutle River (M Tons)	90	127	234	335	175	168	50%	58%

To include mid-range hydrologic and sediment input for forecast modeling, an adjusted 28-year sequence (Sequence B) was developed by selecting a combination of years that closely produces an average exceedance range for all four metrics. The resulting Sequence B was shown in Table 2.6. A comparison of the frequency of occurrence of the surrogate years for Sequence A and Sequence B was provided in Figure 2.13. Table 2.8 provides the results of the bootstrapping of each metric along with a comparison of Sequence A and Sequence B.

Sequence B includes two occurrences of WY 2007, which includes the Nov 2006 event. WY 2007 had the highest sediment loads recorded since the years preceding the eruption of MSH; however, it did not have the highest volumetric water discharge of the 1999 to 2007 time frame. WY 1999 shows the highest annual discharge volume and occurs once in Sequence B, as opposed to six times in Sequence A. Six occurrences of WY 1999 in Sequence A resulted in a high representation of discharge volume. Review of all four metrics used to develop Sequence B shows that WY 2001 had the lowest values of volumetric discharge and sediment loads and occurs twice in the series.

3.0 NORTH FORK TOUTLE RIVER ABOVE THE SRS

After construction of the SRS cofferdam in 1987, the SRS began effectively impounding sediment. Upon completion of the SRS, all water passed the SRS through a pipe array outlet works designed to maintain a relatively small settling pool. As sediment began accumulating in the SRS, pipes in the outlet work were successively closed when they became blocked with sediment. The first flows that bypassed the outlet works and flowed over the spillway occurred in 1996. The final row of outlet works pipes was closed on April 22, 1998 and all flow was routed over the spillway. Deposition levels subsequently reached the elevation of the spillway crest (Figure 3.1). Movement of sediment through the SRS spillway during the past 10 years has resulted in the increased delivery of sediment, specifically medium and coarse sands, to the Cowlitz River. Erosion of material from the debris avalanche flowing through the SRS spillway was estimated by the Sediment Budget to account for approximately 79% of all sources within the Toutle/Cowlitz Basin (see Figure 4.1). The overall trapping efficiency of the sediment plain between 1999 and 2007 was estimated at 37%. Currently there is no definitive evidence suggesting that decay in erosion rates of the debris avalanche is occurring. Continued erosion of the debris avalanche coupled with the geomorphic evolution of the sediment plain will likely result in a change to the quantity and type of sediment flowing through the SRS spillway. Long-term trends in sediment deposition and outflow from the SRS are of significant interest when considering sediment management alternatives within the basin.

Figure 3.1 North Fork Toutle River Looking Upstream from the SRS, May 2009

3.1 Modeling Approach

Sediment transport models using both 1-D HEC-RAS and 2-D MIKE 21C software were developed to determine future trends in sediment deposition and outflow from the SRS through 2035. The 1-D and 2-D models utilized for analysis have common and uncommon advantages and disadvantages. The 2-D model is capable of handling the complex hydrodynamic effects occurring along the wide and braided system located along the sediment plain, however, computational intensity is extremely high resulting in lengthy run times (on the order of weeks) and the need to truncate hydrology to complete long-term modeling in a reasonable project time frame. Conversely, the 1-D model does not handle complex system hydrodynamics in multiple dimensions, although long-term simulations given 1-D system simplifications can be run with relatively short computation times (less than 1 day). Having two tools for analyzing project alternatives is advantageous. Several sediment management alternatives can be quickly screened for viability using the 1-D model. Feasible alternative measures refined using 1-D modeling results can then be further tested with the 2-D model. In addition, the development of two models using very different computation methods resulting in similar results promotes confidence in the modeling outcome.

The 1-D and 2-D models were developed for a calibration period of 3 years between 2003 and 2006 and a long-term forecasting simulation of 28-years from 2007 to 2035. Data provided in the 2010 SBR were used as a framework for upstream inflowing water and sediment conditions. Output from the 1-D and 2-D models will be used as input to downstream modeling schemes.

3.1.1 Model Reach

The *study limits* of the North Fork Toutle FEDS analysis extend from the MSH debris avalanche downstream to the SRS spillway, approximately 11.5 miles. The North Fork Toutle River between Elk Rock and the SRS includes three distinctly different geomorphic zones including:

1) Lower Debris Avalanche Zone: This reach extends along the lower debris avalanche from N1 upstream to Elk Rock and is approximately 5 miles in length with a slope of 0.02 ft/ft. The reach is characterized by multiple migratory narrow channels capable of producing supercritical hydraulic conditions as well as banks that frequently fail by mass wasting. It should be noted that sediment transport equations cannot be appropriately applied to supercritical flow hydraulics. Bed material samples include material ranging from fine sands to small cobbles with a D_{50} of 32 mm (coarse gravel).
2) Upper Sediment Plain: This reach is located on the upper sediment plain extending from N1 downstream approximately 3 miles. This reach exhibits multiple migratory channels with a slope of 0.01 ft/ft with bed material consisting of fine sands up to coarse gravels and a D_{50} between 0.6 mm to 1.8 mm (medium to coarse sands).

3) Lower Sediment Plain: The lower sediment plain extends approximately 3.5 miles upstream from the SRS spillway with a slope of approximately 0.002 ft/ft. The reach is a wide braided system with bed material ranging from silts to coarse sands with a D_{50} between 0.2 to 0.3 mm (fine sands).

The 1-D and 2-D *model limits* extend approximately 9 miles upstream from the SRS spillway to just upstream of N1 (reaches 2 and 3), see Figure 3.2. Inclusion of the lower debris avalanche between Elk Rock and N1 (reach 1) in the mobile-bed sediment transport modeling was found to be infeasible due to the notable difference in reach characteristics relative to the sediment plain. The surface comparisons presented in the 2010 SBR were used as a model for erosion occurring on the lower debris avalanche, which served as input to the sediment transport models at N1.

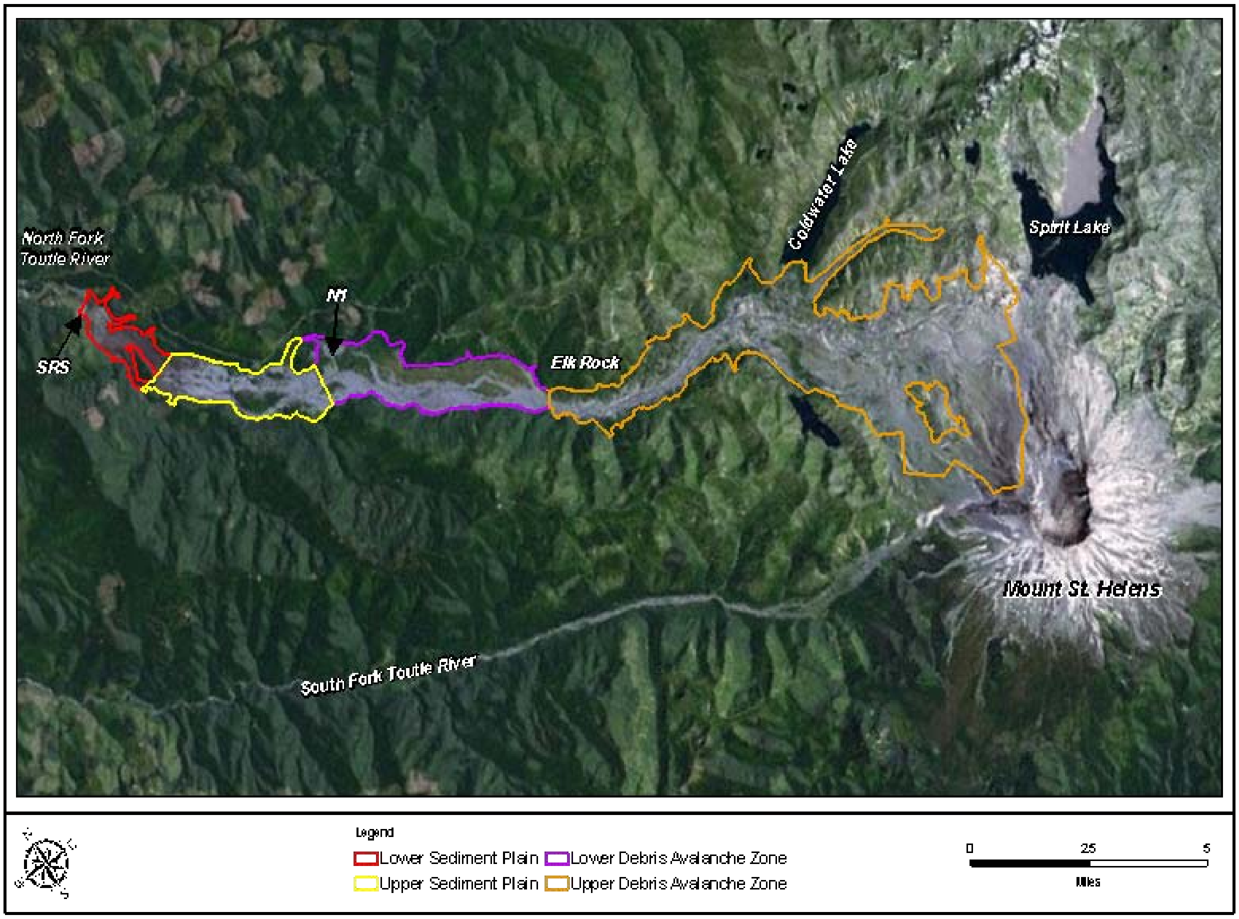

Figure 3.2 North Fork Toutle River above the SRS, 1-D/2-D Model Reach

3.1.2 Calibration

The purpose of calibration is to test performance of a selected model against observed data to confirm model viability for use in long-term forecasting simulations. Models were calibrated to the mass deposition of sediment above the SRS directly measured by comparing LiDAR survey data. Details of the LiDAR survey comparisons utilized to measure deposition can be found in the Sediment Budget Report. Both 1-D and 2-D calibration models were developed for a period of 3 years between Oct 2003 and Sep 2006 (WYs 2004 through 2006) corresponding to the collection of LiDAR survey data in 2003 and 2006. Availability of LiDAR survey data at the beginning and end of the calibration period was a driving factor for selecting the 2003 to 2006 time period. A plot of the annual sediment output from the SRS between 1999 and 2007 is shown in Figure 3.3. The model results were then compared with the 2006 LiDAR surface data corresponding to the end of the calibration period.

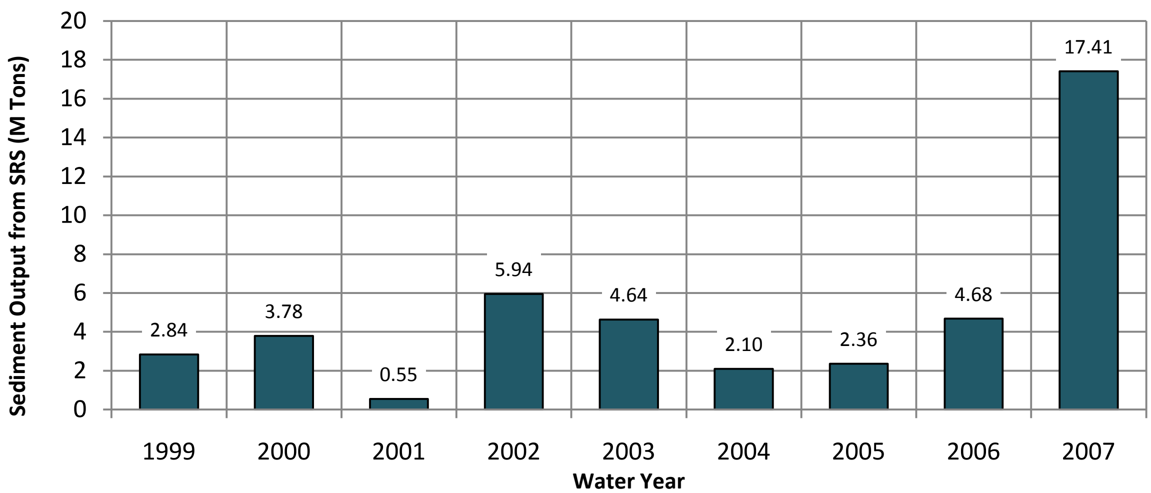

Figure 3.3 Annual Sediment Output from the SRS between 1999 and 2007 (from the 2010 SBR)

3.1.3 Long-term Forecasting

Long-term forecasting 1-D and 2-D models were developed in order to predict future trends in sediment output and trapping efficiency of the SRS. The long-term forecasting models were developed to simulate 28 years between 2007 and 2035 using the hydrologic sequence presented in Section 2.3. Starting geometry was developed using 2007 LiDAR survey data.

3.2 1-D HEC-RAS Model

The 1-D modeling was conducted using an updated (Beta) Version 4.1 of the USACE's HEC-RAS software provided by the Hydrologic Engineering Center in Nov of 2009. HEC-RAS is a

quasi-unsteady, mobile boundary, 1-D sediment transport model. Input to the model includes hydrologic time series, channel geometry, bed material gradations, downstream boundary conditions, and inflowing sediment load.

3.2.1 Model Development

3.2.1.1 Model geometry

LiDAR survey data collected in Oct of 2003, 2006, and 2007 through contract by the Portland District were used in the Sediment Budget to directly calculate volumes of erosion and deposition occurring above the SRS. A detailed discussion of the surface comparisons and results is provided in Section 4.3 of the 2010 SBR. All LiDAR data sets reference the Washington State Plane Coordinate System South with units in survey feet and the vertical datum of NAVD88.

Cross sections cut from the 2003 LiDAR survey data (USGS 2003; data collection by EarthData International) with the USACE HEC-GeoRAS extension in Geographic Information System (GIS) were used as input to the calibration model. Cross sections were cut at a spacing of approximately 500 to 1,000 ft. Portions of the study reach exhibit braided channels including numerous split flow paths. Major flow paths identified from the survey were included in the modeling. The model geometry and flow network include the major split flow occurring around the large island located near the SRS. It was impractical to attempt to model all small split flow channels, which are highly migratory, in the braided portions of the study reach. These small split flow channels are active during low flows in which a majority of the sediment transport is not occurring. Split flow analyses were not performed on smaller braided channel networks.

For calibration purposes, cross sections were also cut using the 2006 LiDAR survey data (USACE 2006a; data collection by Watershed Sciences) at the same locations as the cross sections developed from the 2003 LiDAR data. Cross sections cut with 2003 and 2006 LiDAR data were used to determine the mass change occurring through the study reach over the 3-year time period. Mass change computed by the end area method was used to calibrate the mass change produced by the 1-D mobile-bed model. Calibration model cross sections and stationing are shown in Figure 3.4.

The long-term forecasting model cross sections were cut using 2007 LiDAR survey data (USACE 2007a; data collection by Watershed Sciences). Figure 3.5 shows the layout and stationing of the 2007 cross sections which, although in the same location as the cross sections cut from the 2003 LiDAR, are positioned with a slightly different orientation and extents based on a differing terrain from the 2003 LiDAR data.

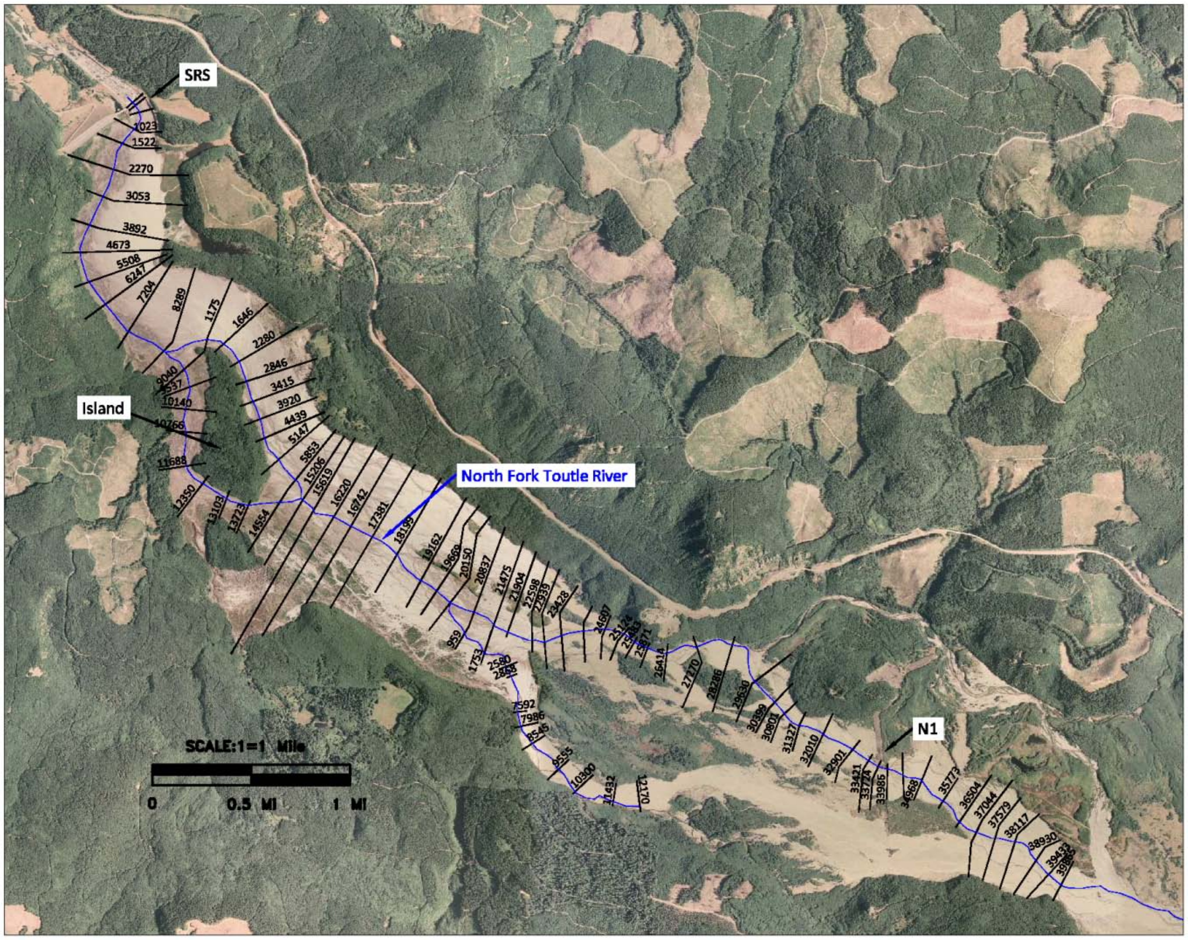

Figure 3.4 Layout of Cross Section Cut with 2003 LiDAR Data for Calibration Model

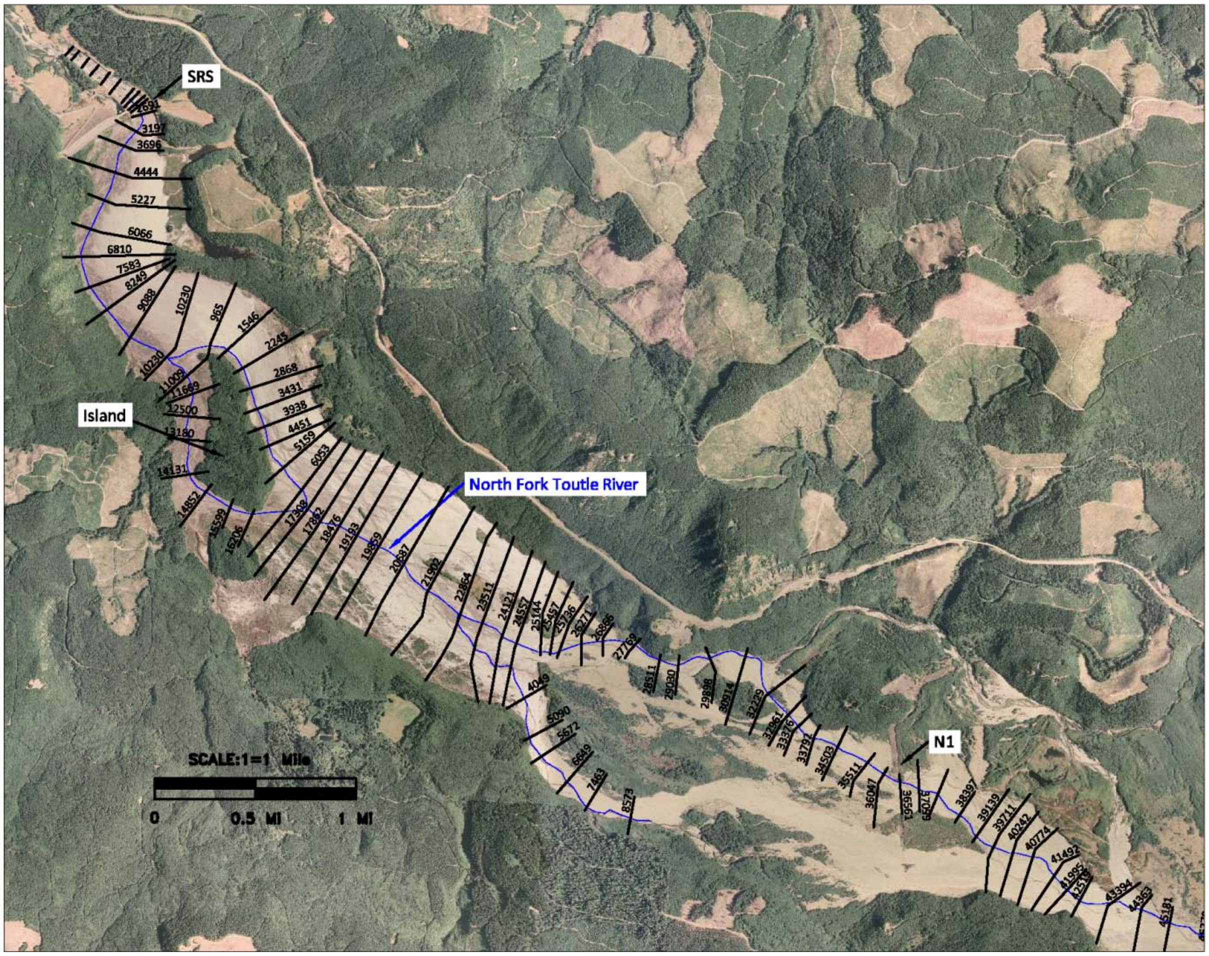

Figure 3.5 Layout of Cross Sections Cut with 2007 LiDAR Data for Forecast Model

Channel roughness used in the model is based primarily on grain roughness. Mean grain sizes coarsen upstream from fine to coarse sands at the SRS to gravels and cobbles near N1. Based on these grain sizes, the roughness ranges from 0.035 at N1 to 0.017 near the SRS. Figure 3.6 is an aerial map of the model limits showing the spatial limits of the roughness coefficients.

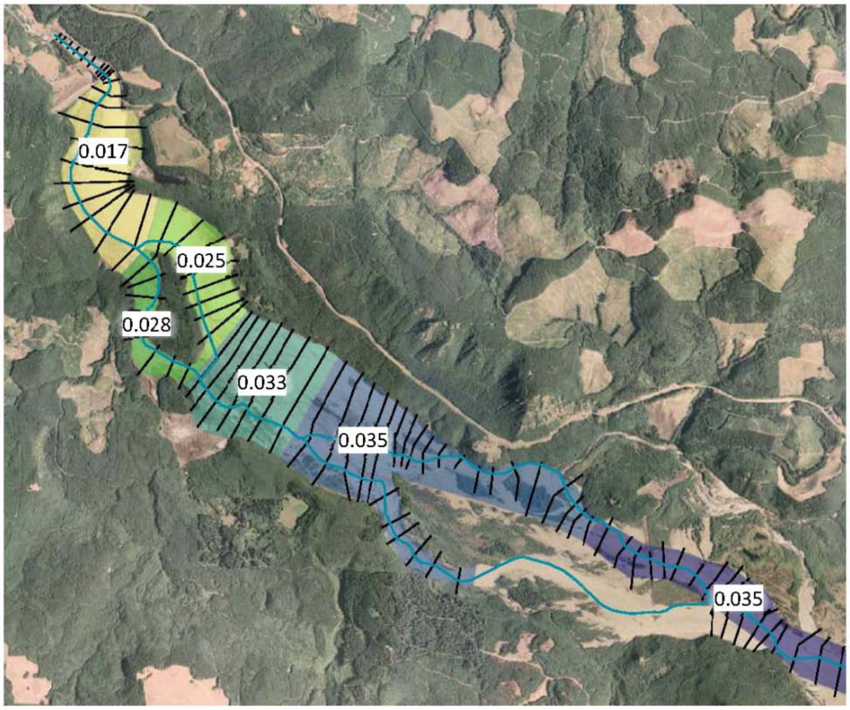

Figure 3.6 Map of Selected Manning's *n* Values

3.2.1.2 Downstream boundary conditions

The SRS spillway (Figure 3.7) provides an ideal downstream boundary condition for sediment modeling. The 400-ft wide concrete spillway maintains a constant crest elevation and geometry as well as providing a consistent hydraulic condition. Normal depth boundary conditions were applied to the downstream cross section of the model, which results in critical depth computations at the spillway crest.

Figure 3.7 SRS Spillway Looking Downstream

3.2.1.3 Bed material

Sediment samples taken by the USACE after 1988 and compiled in hydrologic summary reports (USACE 1988 to 2004) along with samples collected by the Biedenharn Group, LLC (2010 SBR) were analyzed for use in the Sediment Budget; see Section 4.5 of the 2010 SBR.   Five samples that best represent reaches of the North Fork above the SRS were selected for input to the 1-D model. The five bed material samples are consistent with the gradations applied in the sediment budget calculations. Bed material gradations applied to the modeling are provided graphically and spatially in Figure 3.8 and Figure 3.9, respectively.

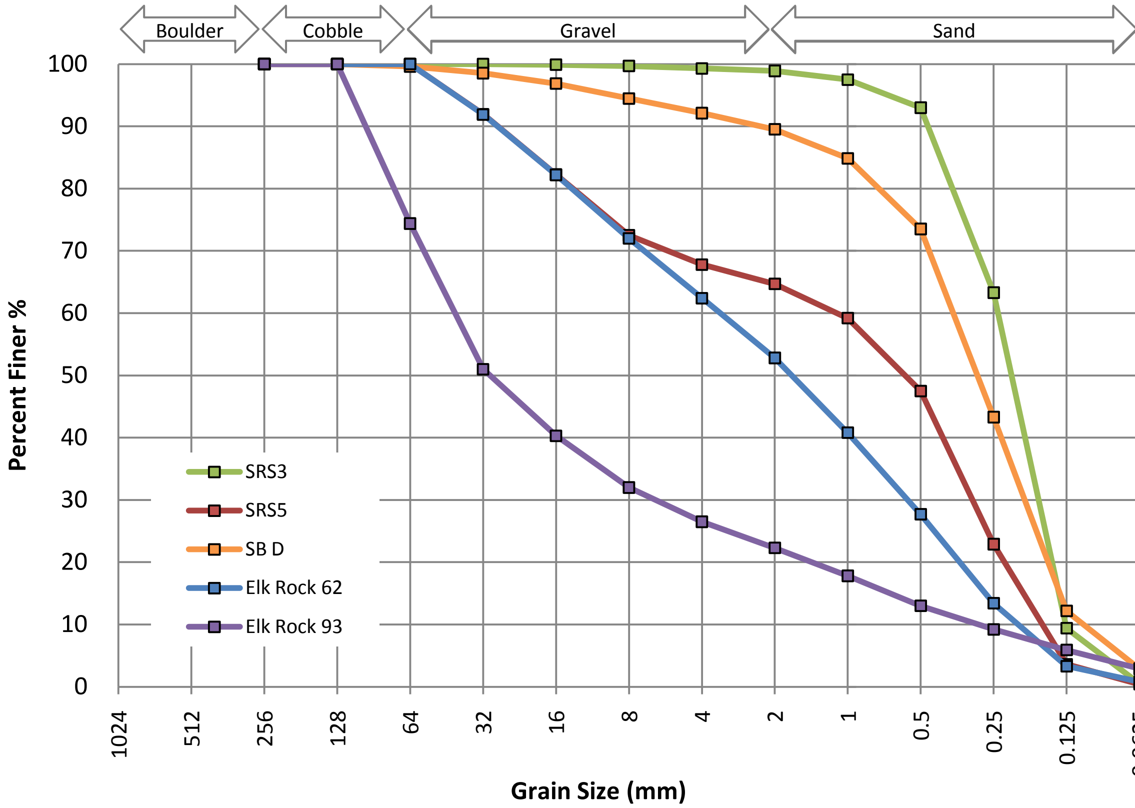

Figure 3.8 Bed Material Gradations (see Figure 3.9 for plan view map)

Figure 3.9 Location of Bed Material Gradations Applied to Modeling (color coding for samples correlates to data in Figure 3.8)

3.2.1.4 Inflowing sediment load

Annual estimates of sediment erosion from the debris avalanche upstream of N1 were calculated using digital surface comparisons, which are summarized in Section 4.3 of the 2010 SBR. The total net erosion during WYs 1999 through 2007 upstream of N1 was estimated to be 72 Million Tons (M Tons). The total value of erosion calculated upstream of N1 includes values presented in the 2010 SBR for sub-areas labeled Coldwater Creek, Castle Creek, Loowit Creek, and Sub-Area A. Annual erosion values for WYs 1999 through 2007 upstream of N1 are presented in Figure 3.10. Variability in the surface comparison results is discussed in Section 4.3.2 of the 2010 SBR. In general, the accuracy of estimates of erosion occurring upstream of N1 was estimated at ±15%.

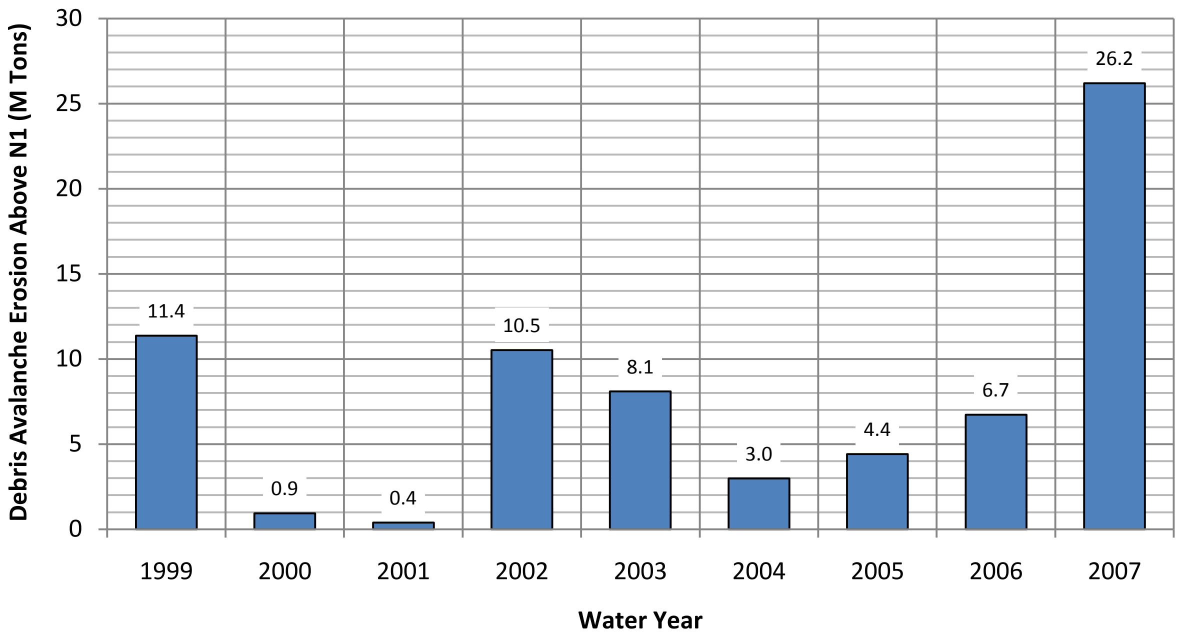

Figure 3.10 Annual Debris Avalanche Erosion Upstream of N1 (from the 2010 SBR)

Distribution of the annual sediment load at N1 into daily values was conducted using trends in suspended sediment data measured at the USGS gage below the SRS. Daily sediment discharge data at the North Fork Toutle gage below the SRS were limited and a rating curve, in the form of a power function, was fit to the available gage data (see Figure 3.11). The form of the sediment rating curve at the SRS was used to develop sediment rating curves at N1. Individual rating curves at N1 were developed to distribute the annual sediment load at N1 for 1999 through 2007. The power of the SRS sediment rating curve (2.28) was applied to the rating curves at N1 in order to maintain the sediment trends associated with discharge. The magnitude of the inflowing sediment load computed at N1 was then adjusted by modifying the coefficient of the power function. The coefficient of the rating curve at N1 was modified until the annual sediment yield of the curve matched the desired annual load specified in Figure 3.10.

Application of different coefficients for various years ensures that the inflowing sediment load for a given year is exactly equal to the value specified by the sediment budget. The resulting inflowing sediment rating curves, one for each water year between 1999 and 2007, are presented in Figure 3.12. Generally, the inflowing rating curves at N1 are the same for most years with the exception of WYs 2000, 2001, and 2007, which represent low and high years of sediment yield.

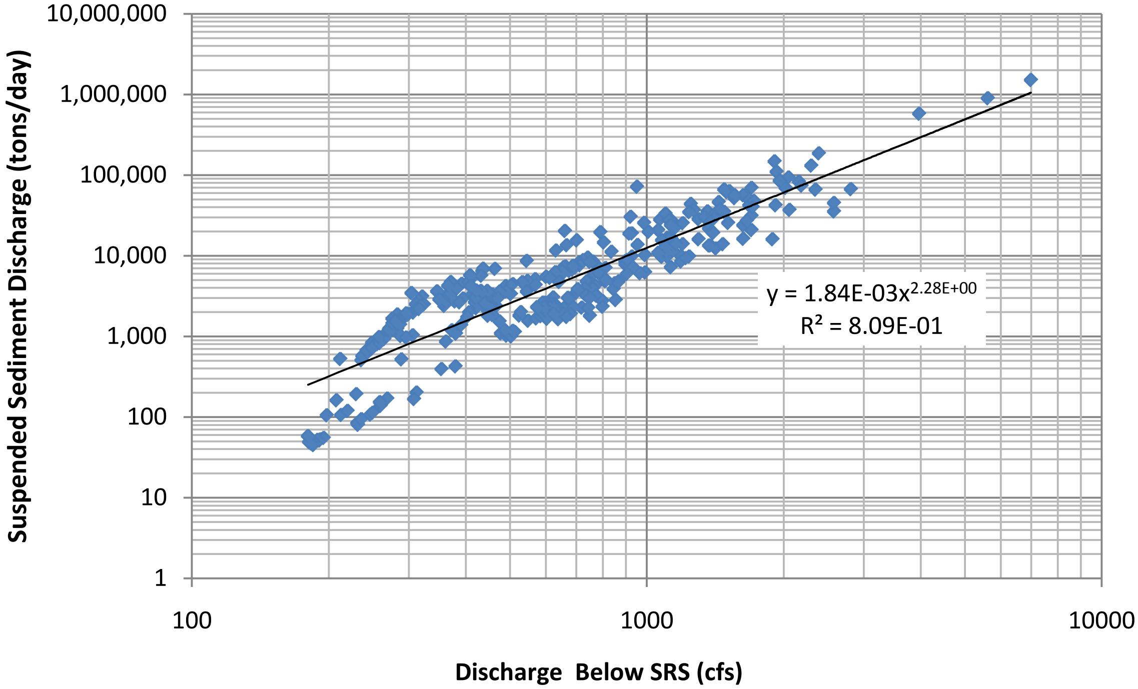

Figure 3.11 USGS Suspended Sediment Gage Data, North Fork Toulte River below the SRS

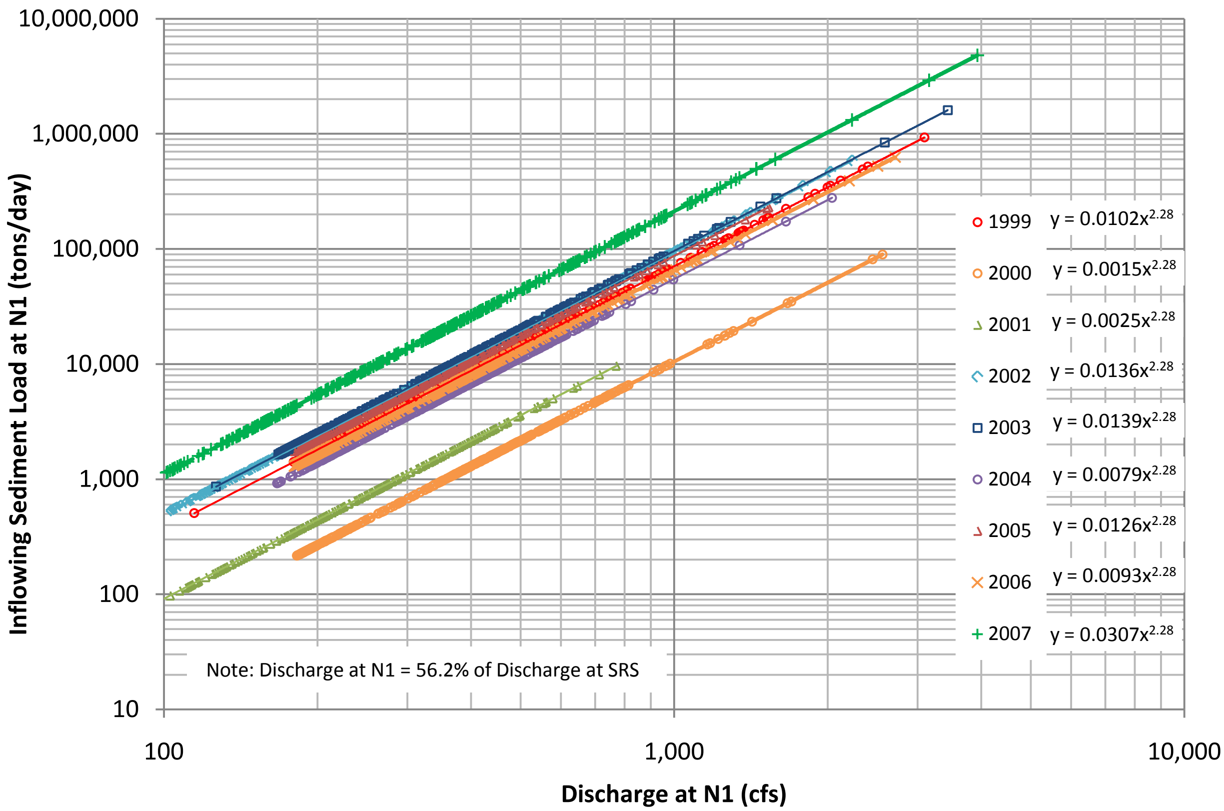

Figure 3.12 Inflowing Sediment at N1 vs. Discharge Rating Curves

The gradation of the inflowing sediment load was developed using a combination of suspended sediment gradation samples collected by the USGS at N1 between 2004 and 2008 and bed material gradation samples presented in the 2010 SBR. Inflowing sediment gradations were varied and coarsened with increase in discharge and sediment load. For low discharges the inflowing sediment gradations are similar to the USGS samples. As discharge increases, the inflowing gradations move towards the bed material gradation found downstream of N1 as USGS samples were not available at higher discharges. Figure 3.13 provides a plot of inflowing sediment gradations for select discharges as well as the USGS suspended sediment samples collected at N1 and the bed material sample SRS5. Development of the inflowing sediment gradations was intended to closely match the overall composite gradation of material eroding upstream of N1 developed for the Sediment Budget. The overall gradation of the total sediment load input to the calibration model at N1 was found to have very close agreement with the gradation used in the Sediment Budget, see Figure 3.14. Although there may be other methods to generate gradation of inflowing sediment it was determined that the developed input produced reasonable calibration results. The 2010 SBR states that identification of sediment volumes by gradation has a high degree of uncertainty.

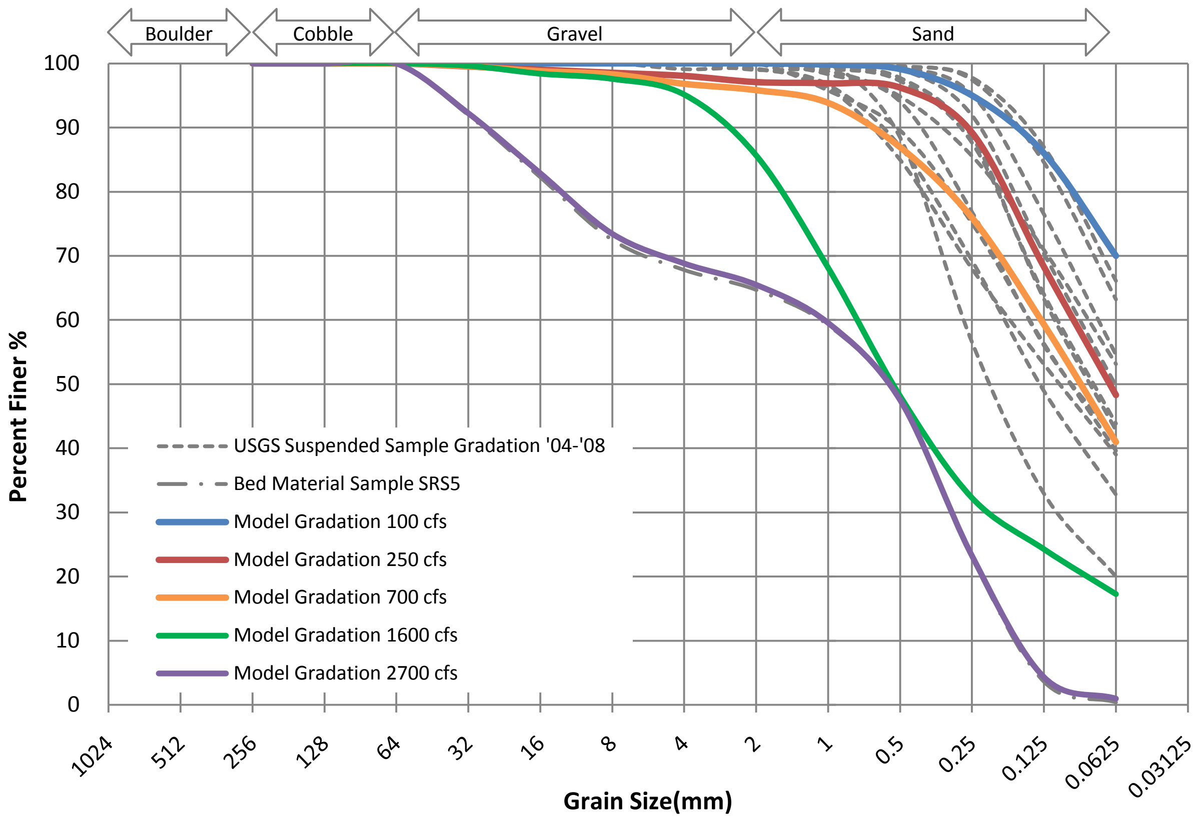

Figure 3.13 Inflowing Sediment Gradation Input at N1 by Discharge, USGS Suspended Sediment Sample Gradations Collected between 2004 and 2008 at N1, Bed Material Sample below N1

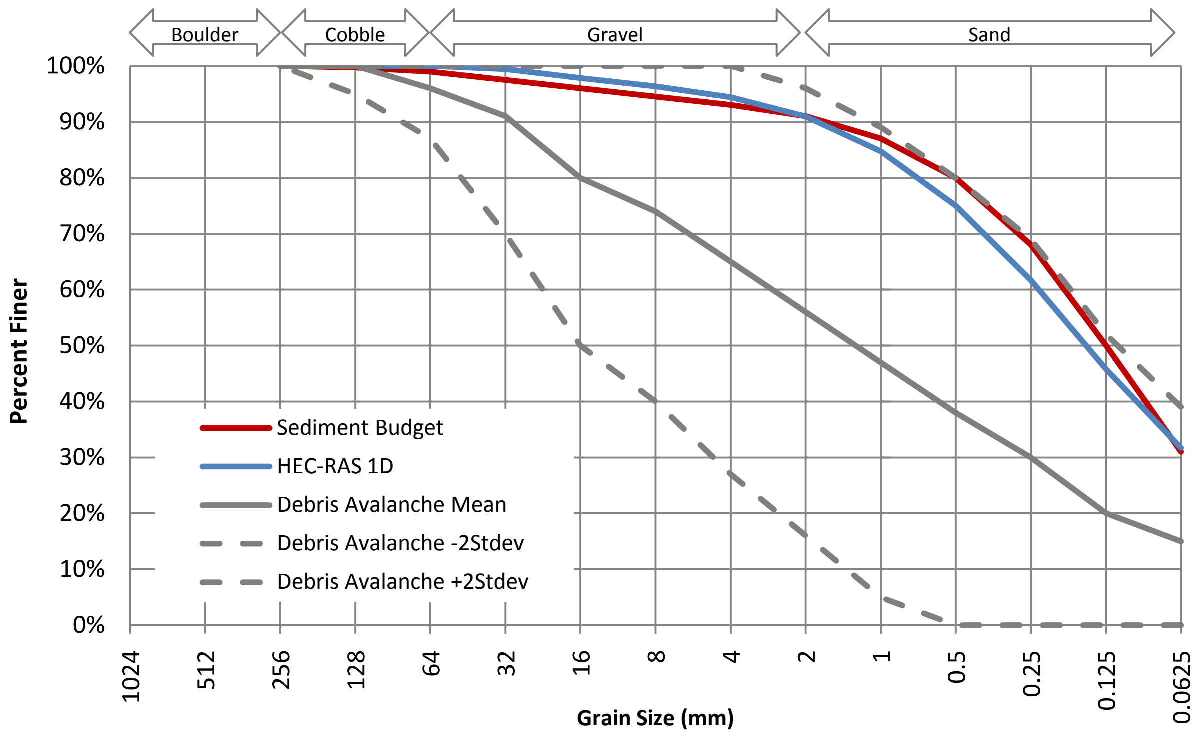

Figure 3.14 Model Gradation of Total Sediment Input at N1 and Gradation of Debris Avalanche Erosion Material (from the 2010 SBR)

3.2.1.5 Model time series/hydrologic simplification

Split flow computations on the cross sections cut from LiDAR information are limited to the main channel. Smaller secondary channels, which develop split flow patterns for low-flow conditions, were not analyzed using the HEC-RAS split flow routine. This simplification assumes that sediment transport during these low flows is negligible. Additionally, a time series and hydrologic simplification was applied to the HEC-RAS 1-D calibration and long-term forecasting models to eliminate flow rates below a defined threshold. The time series discharge hydrograph was truncated to exclude discharge equal to or less than 600 cfs at the SRS spillway. Figure 3.15 shows the daily average discharge hydrographs on the North Fork below the SRS for WYs 1999 through 2007 utilized in the forecasting sequence and the calibration period (WYs 2004 through 2006). The estimated inflowing sediment load for flow less than 600 cfs accounts for approximately 10% of the total sediment load input at N1 for both the calibration period and long-term forecasting sequence. It is expected that the excluded load consists of predominantly finer material that is not found in quantity in the bed of the Lower Cowlitz River. Exclusion of 10% of the inflowing sediment load to the model was deemed to be well within the limits of uncertainty.

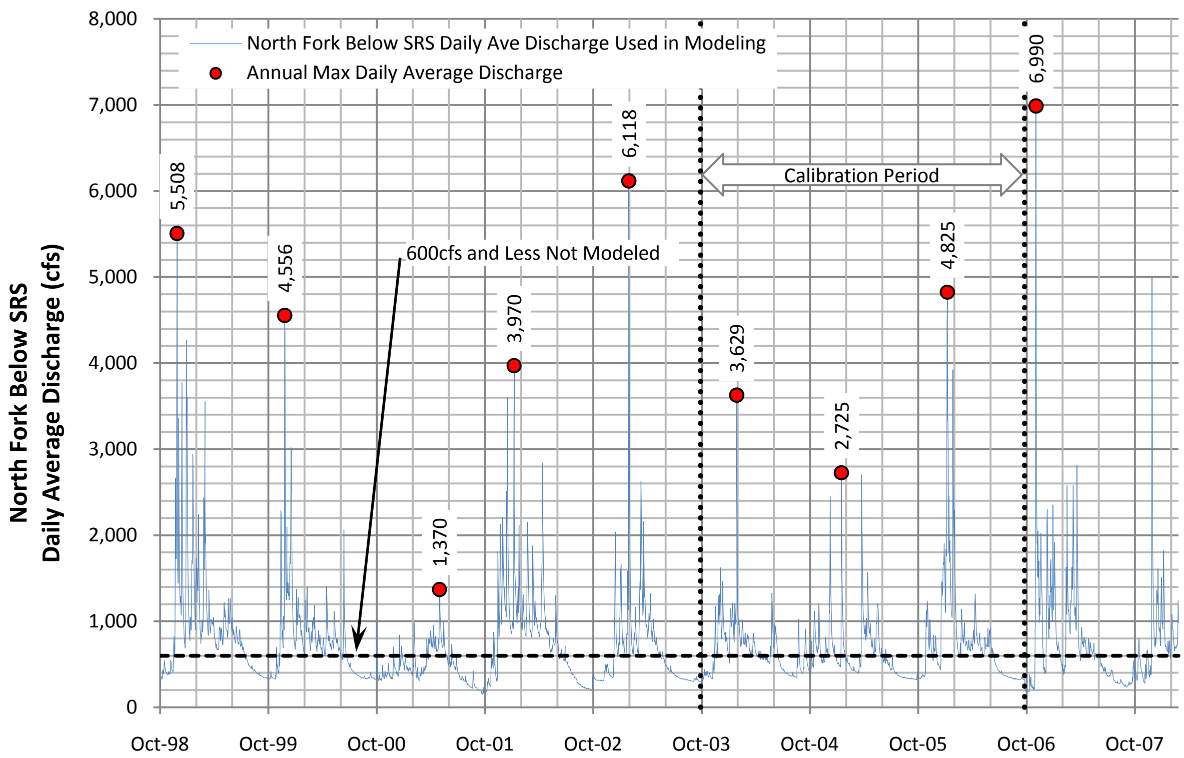

Figure 3.15 North Fork below the SRS Daily Average Discharge Data, WYs 1999 through 2007

3.2.2 Calibration

The 1-D calibration model was developed and run for the 3-year period between Oct 2003 and Sep 2006, corresponding to the 2003 and 2006 LiDAR survey data.

3.2.2.1 Survey data

Model cross sections developed using 2003 and 2006 LiDAR data were used to compute the observed mass bed change along the model reach during the 3-year period, which was used as the performance metric for model calibration. Mass bed change at each cross section was computed using the end-area method allowing for a direct spatial comparison to HEC-RAS model output. Comparison of the complete LiDAR surface digitally using GIS was conducted and presented in Section 4.3 of the 2010 SBR. The total mass bed change between N1 and the SRS computed digitally from LiDAR was 5.01 M Tons (net deposition) assuming an *in-situ* density of 95 lbs/ft^3. The total mass bed change for the entire study reach calculated using the end-area method was found to be 4.86 M Tons (net deposition), a 2.9% difference when compared to the digital LiDAR surface computation. A graphical representation of the mass bed change computed using cross sections is provided in Figure 3.16. Cumulative mass bed change in the downstream direction computed by cross-section data is shown in Figure 3.17.

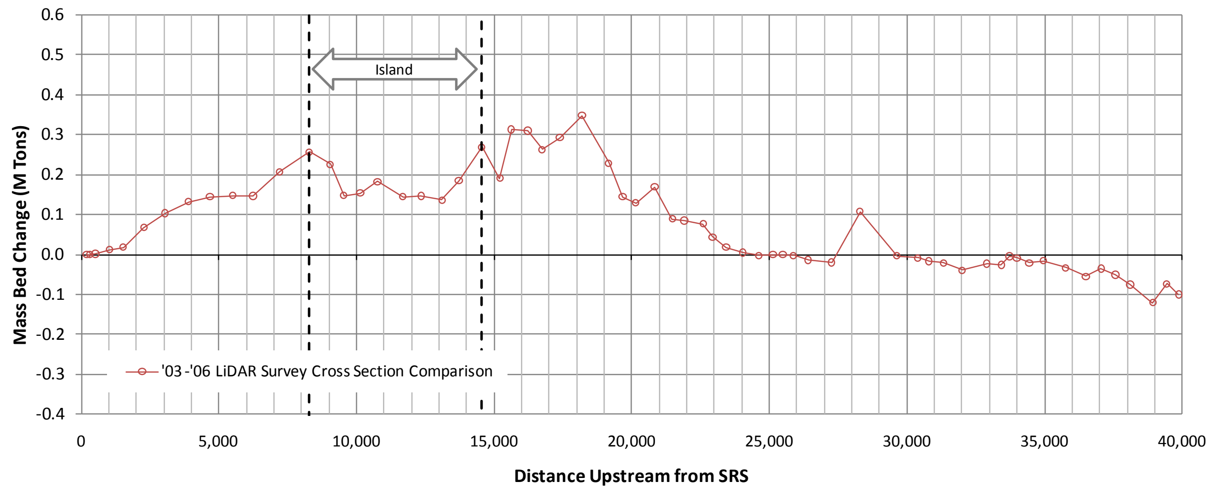

Figure 3.16 Observed Mass Bed Change above the SRS between Oct 2003 and Sep 2006 Computed by Cross-section End Area Method (see Figure 3.4 for plan view map)

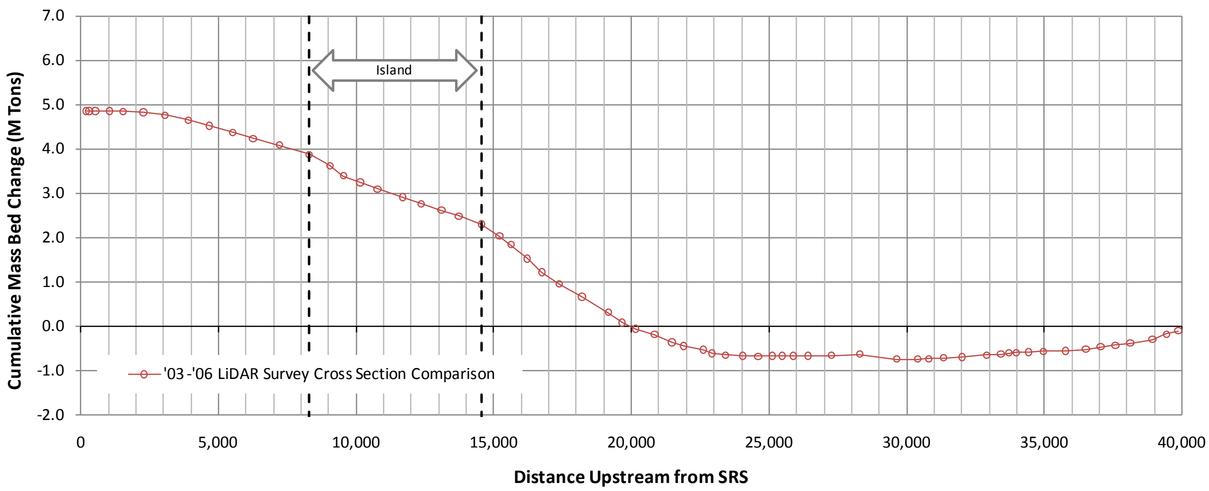

Figure 3.17 Longitudinal Cumulative Mass Bed Change above the SRS between Oct 2003 and Sep 2006 Computed by Cross-section End Area Method (see Figure 3.4 for plan view map)

3.2.2.2 Sediment transport equation

The Laursen-Copeland sediment transport equation was selected to be used for modeling based upon its applicability to a large range of sediment sizes and its efficiency in transporting large amounts of sand, both of which are conditions present above the SRS. The Laursen-Copeland transport equation is a total load equation consisting of an excess grain shear type computation to determine the sediment discharge concentration. The formulation of the Laursen-Copeland equation used in HEC-RAS is shown in Equation 3.1 (USACE 2010):

Laursen-Copeland: $$C_m = 0.01\gamma\left(\frac{d_s}{D}\right)^{7/6}\left(\frac{\tau' - \tau_c}{\tau_c}\right) f\left(\frac{u_*}{\omega}\right)$$ **Equation 3.1**

where,

C_m	=	sediment discharge concentration (weight/volume);
γ	=	unit weight of water (weight/volume);
d_s	=	mean particle diameter (L);
D	=	effective depth of flow (L);
τ'	=	bed shear due to grain resistance (pressure);
τ_c	=	critical bed shear stress (pressure); and
$f\left(\frac{u_*}{\omega}\right)$	=	empirical function, where u_* is shear velocity (L/T) and ω is fall velocity (L/T).

There are several other sediment transport functions to choose from in HEC-RAS, some of which were tested during calibration to ensure that the selection of Laursen-Copeland was appropriate. Results of model runs using the default forms of Yang, Ackers White, and Laursen-Copeland are compared graphically in Figure 3.18. Ackers White tends to underestimate deposition, while the Yang equation overestimates deposition. The default form of the Laursen-Copeland equation also overestimates deposition, however, the shape of the cumulative mass bed change follows the trend of the observed data quite well. Further modification of variables within the Laursen-Copeland equation was conducted in order to more closely match observed data.

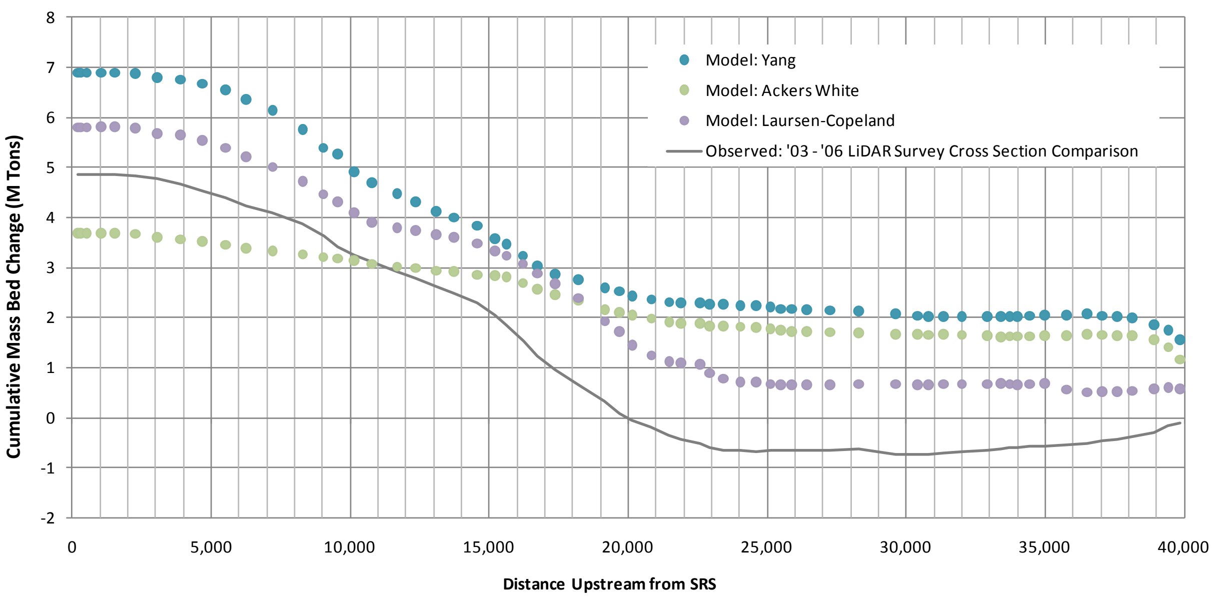

Figure 3.18 Calibration Model Results Using Various Default Sediment Transport Equations

The updated (Beta) Version 4.1 of the USACE's HEC-RAS software used for this study includes a transport function calibration feature that exposes equation variables such as the critical shear stress (default value = 0.039), transport coefficient (default value = 0.01), and power of the transport engine or excess grain shear computation (default value = 1.0). Exposure of transport function variables is extremely helpful in allowing for more flexibility when conducting a calibration.

Modification of the critical shear stress, transport coefficient, and power of transport were explored during model calibration. To gain insight into the effects of modifying each exposed variable, the following range of values were tested individually, while keeping the remaining values at default levels:

- Critical Shear Stress: 0.02 to 0.06 (default 0.039)
- Transport Coefficient: 0.002 to 0.05 (default 0.01)
- Power of Transport: 0.9 to 1.5 (default 1.0)

Calibration model results of runs with varying critical shear stress, transport coefficient, and power of transport are shown in Figure 3.19, Figure 3.20, and Figure 3.21, respectively.

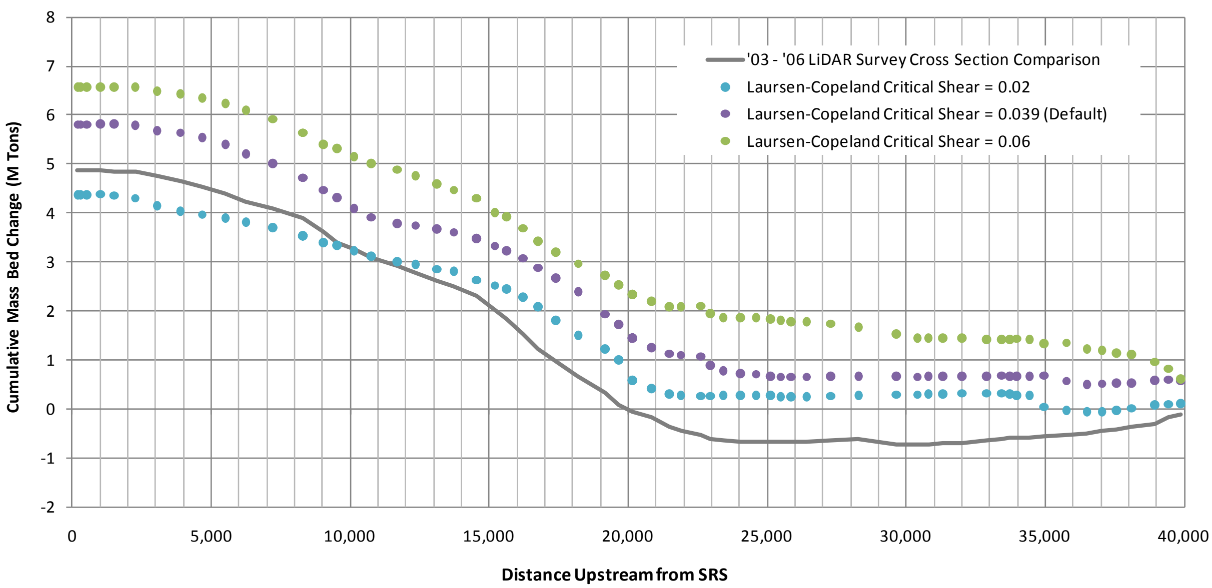

Figure 3.19 Calibration Model Results with Laursen-Copeland and Varying Critical Shear Stresses

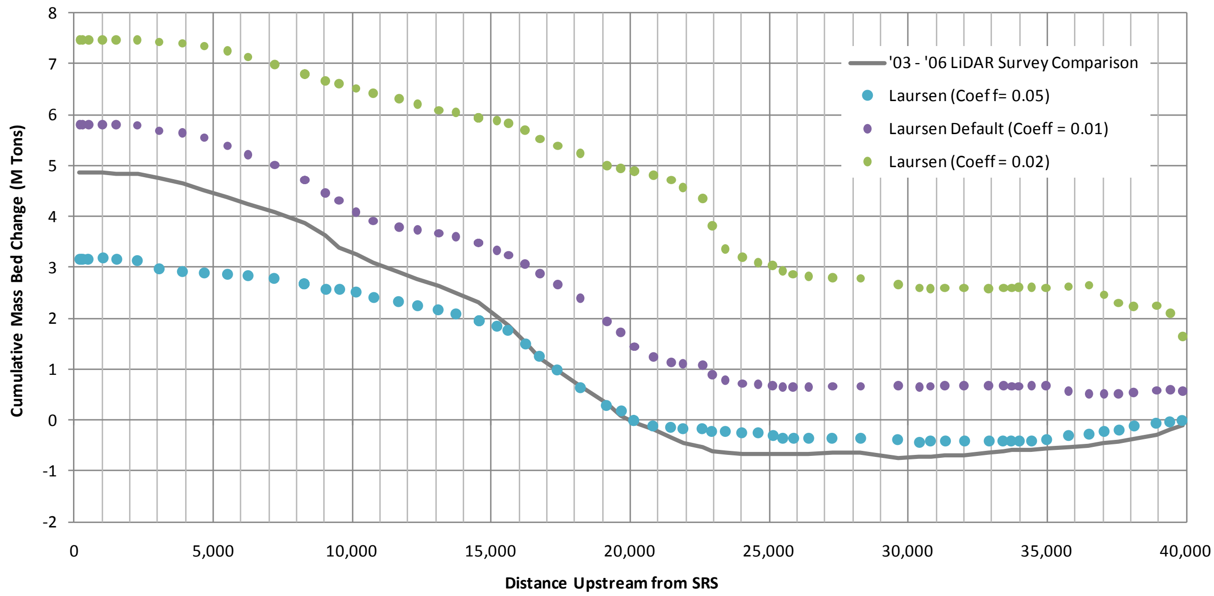

Figure 3.20 Calibration Model Results with Laursen-Copeland and Varying Transport Coefficients

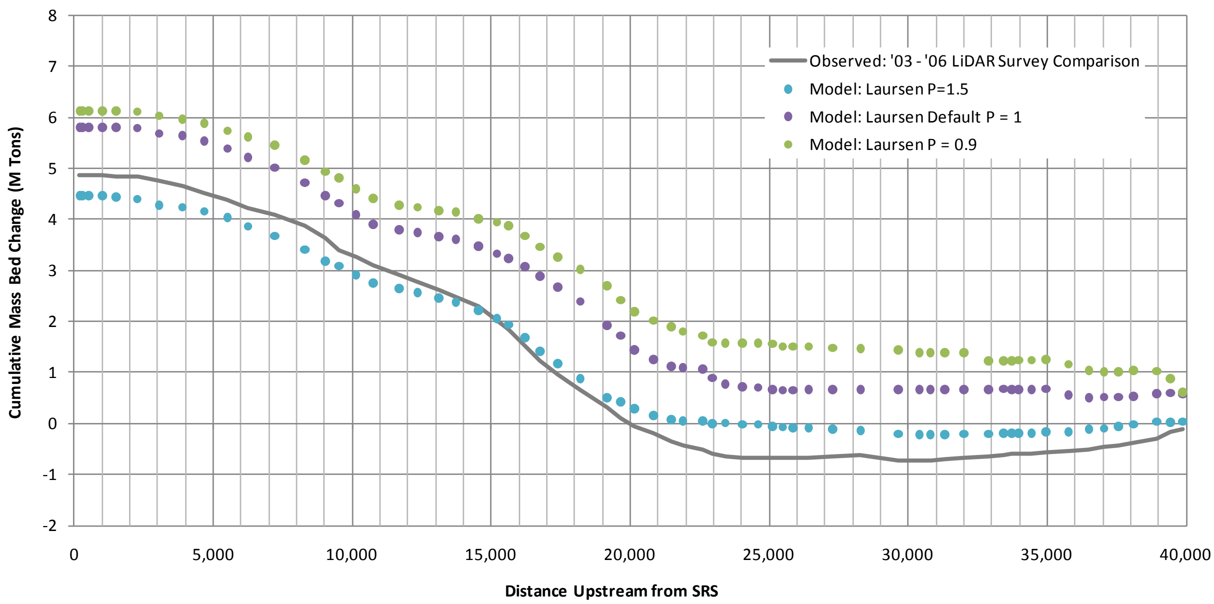

Figure 3.21 Calibration Model Results with Laursen-Copeland and Varying Power of Transport

Exposed variables were modified as little as possible from their default values, while still matching calibration parameters within reason. The final form of the Laursen-Copeland equation selected for use includes the default values for critical shear (0.039), the default coefficient (0.01), and an increase in the power function from a default value of 1.0 to 1.4.

Figure 3.21 shows a comparison of the cumulative mass bed change measured using survey data and several calibration model results for different forms of the Laursen-Copeland equation.

3.2.2.3 *Final calibration results*

Calibration model results were checked spatially against the 2003 to 2006 survey data cross-section comparison. A comparison of the total mass bed change at each cross section is provided in Figure 3.22. Figure 3.23 shows a comparison of the cumulative mass bed change from model results and cross-section survey data.

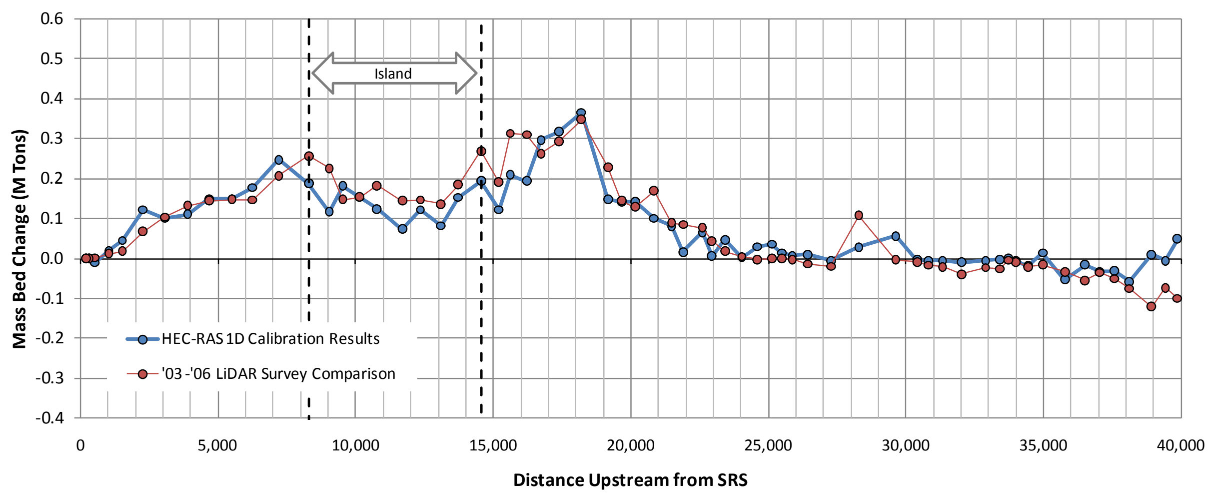

Figure 3.22 Mass Bed Change, HEC-RAS 1-D Calibration Results vs. Survey Data (see Figure 3.2 for plan view map)

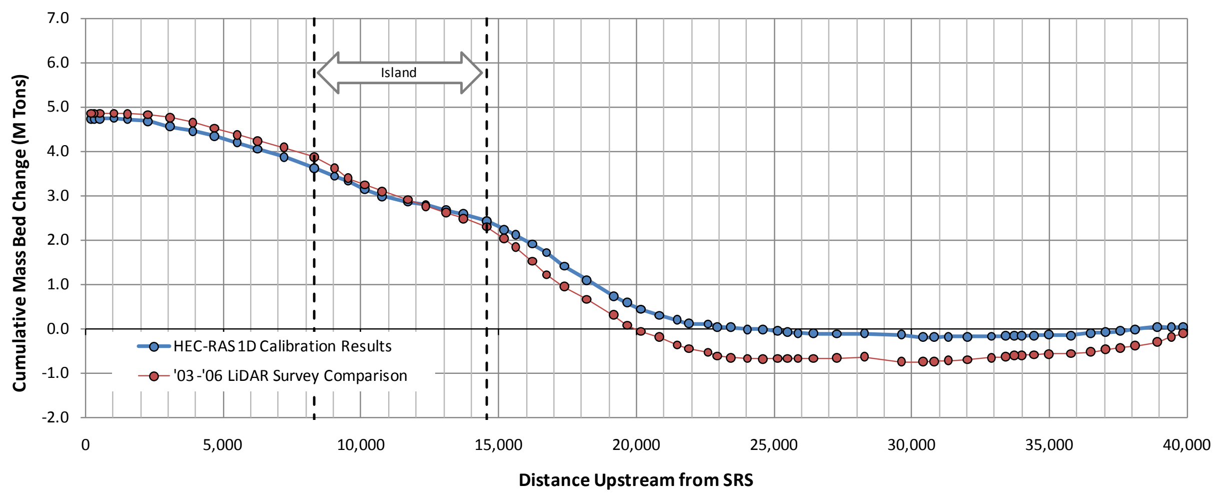

Figure 3.23 Cumulative Mass Bed Change, HEC-RAS 1-D Calibration Results vs. Survey Data (see Figure 3.2 for plan view map)

The total mass bed change computed by the final calibration model was 4.88 M Tons of deposition, which when compared to the observed data is within 2.6%, see Table 3.1.

Table 3.1 Cumulative Mass Bed Change from N1 to the SRS, 2003 to 2006

Analysis	Total Mass Bed Change 2003 to 2006 (M Tons)	Percent Difference from LiDAR Surface Comparison
2003 to 2006 LiDAR Surface Comparison (Sediment Budget)	5.01	n/a [A]
2003 to 2006 Cross-section End Area Method Comparison	4.86	2.9%
HEC-RAS 1-D Calibration Model Results	4.88	2.6%

[A] n/a = not applicable

Sediment output by grain class was also checked against the results of the Sediment Budget for the calibration period. Figure 3.24 shows the total sediment output by grain class computed by the Sediment Budget and HEC-RAS 1-D model. It should be noted that estimates by grain class provided in the Sediment Budget have a reasonably high value of uncertainty.

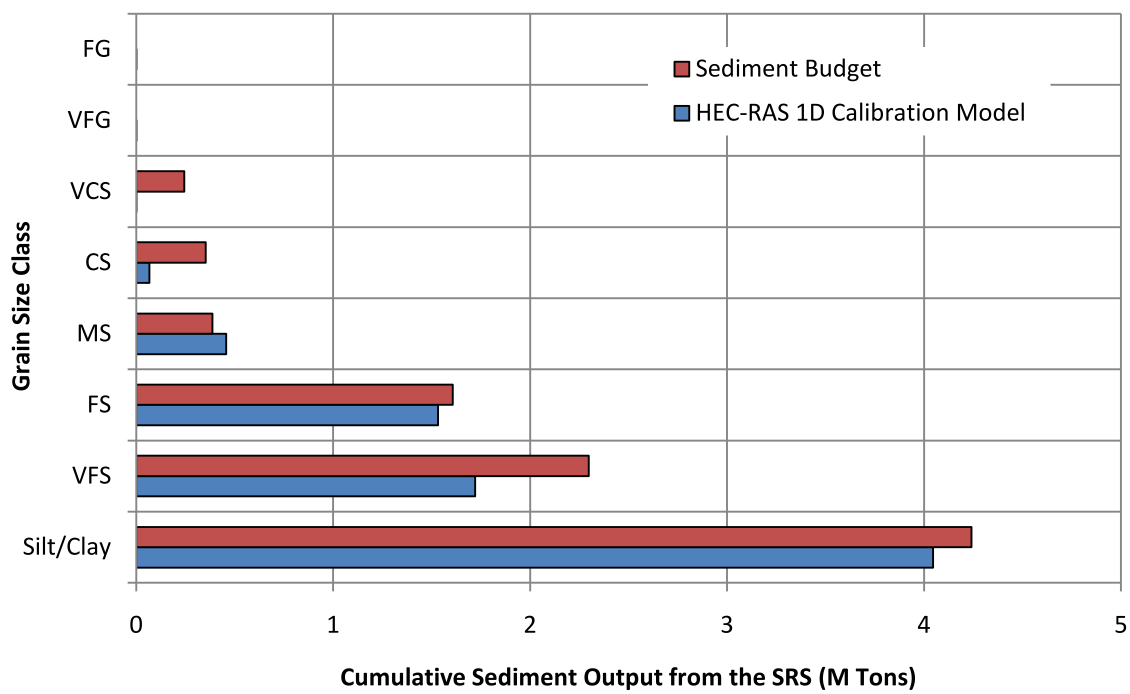

Figure 3.24 Cumulative Sediment Output from the SRS by Grain Size for Calibration Period 2003 to 2006, Sediment Budget vs. HEC-RAS 1-D Calibration Model Results

3.2.3 Long-term Forecasting Results

Cumulative sediment input to the model at N1, sediment deposition, and sediment output flowing over the SRS spillway through the long-term forecast is shown in Figure 3.25. Results of the HEC-RAS 1-D model in 2035 show a total inflow of 201 M Tons, deposition of 50 M Tons, and sediment output of 152 M Tons. The large increase in sediment input and output occurring in WY 2015 and 2030 represents the occurrence of surrogate WY 2007. Given the large inflow of the WY 2007 event, the model shows significant deposition. Efficient deposition occurring during the peak event in the model is due to the valley wide spread of flow, which increases wetted perimeter and decreases in velocity allowing for more efficient deposition.

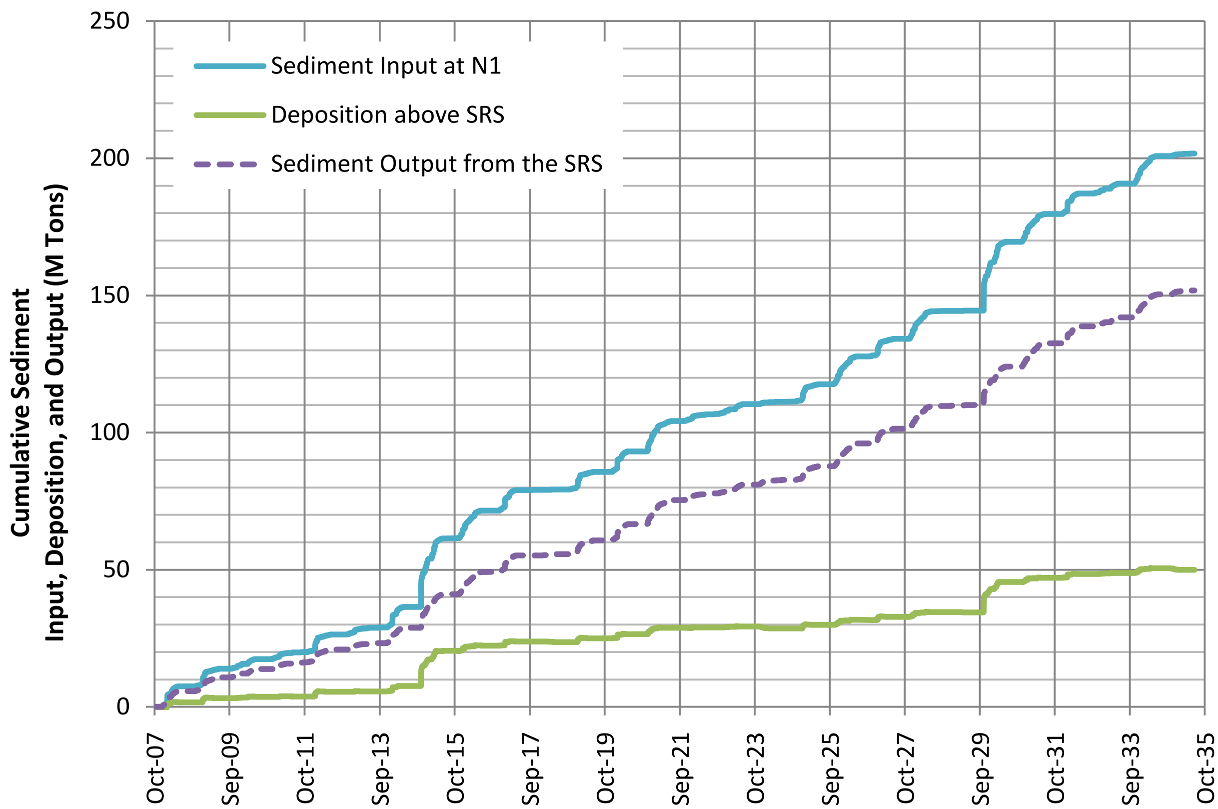

Figure 3.25 Cumulative Sediment Input, Deposition, and Output through 2035

A comparison of the sediment output from the SRS from results of 1-D modeling and a forecast using the sediment budget estimates is provided in Figure 3.26. Note that forecasting estimates using sediment budget values assume that there is no decrease in the trapping efficiency of the sediment plain through time. Comparison of the cumulative sediment output plotted in Figure 3.26 shows that the 1-D model closely matches the sediment budget numbers until 2018 after which the lines begin to deviate. This is due to the decrease in overall trapping efficiency of the sediment plain over time within the 1-D model.

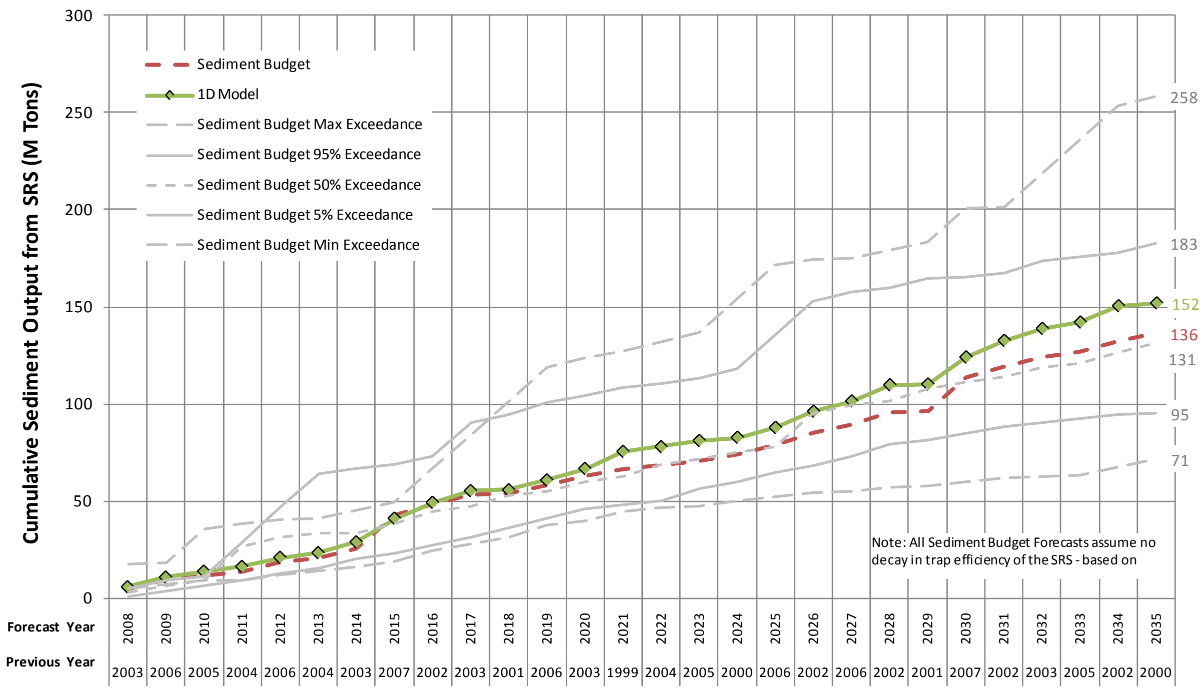

Figure 3.26 1-D Model and Sediment Budget Cumulative Sediment Output from the SRS through 2035

Cumulative mass bed change from upstream to downstream at the end of the forecast period is shown in Figure 3.27. A majority of deposition occurs around and upstream of the large island. Deposition just upstream of the SRS spillway was found to be little to none.

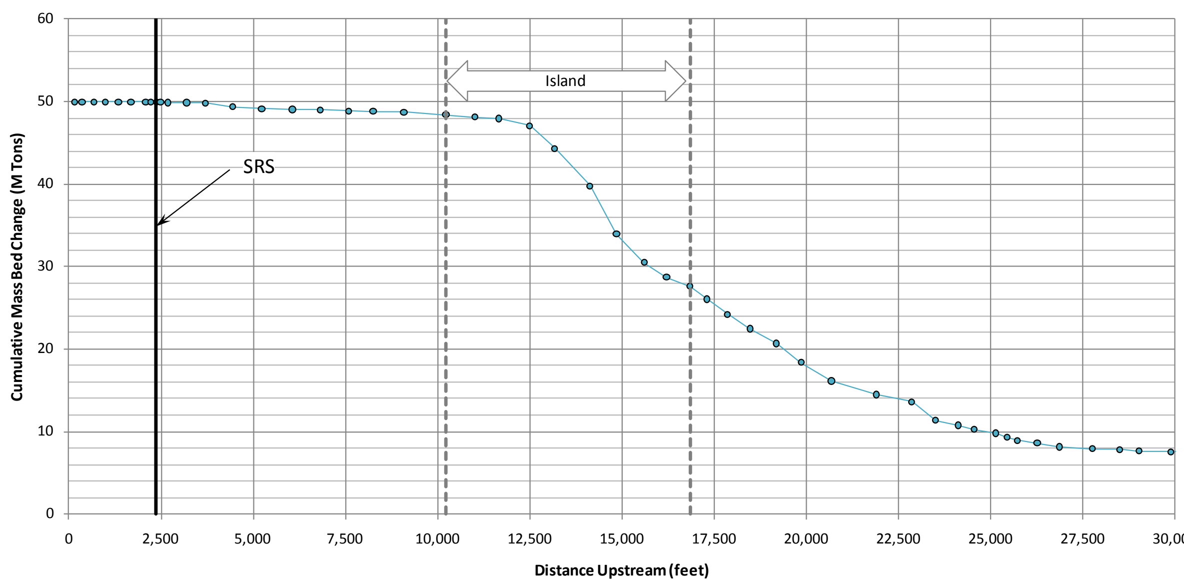

Figure 3.27 Cumulative Mass Bed Change vs. Distance Upstream (see Figure 3.5 for plan view map)

A profile of the average elevation along the valley wide cross sections at the start and end of the long-term forecast run is provided in Figure 3.28 along the main flow path around the left side of island. Figure 3.29 shows the before and after profile computed around the right side of the island.

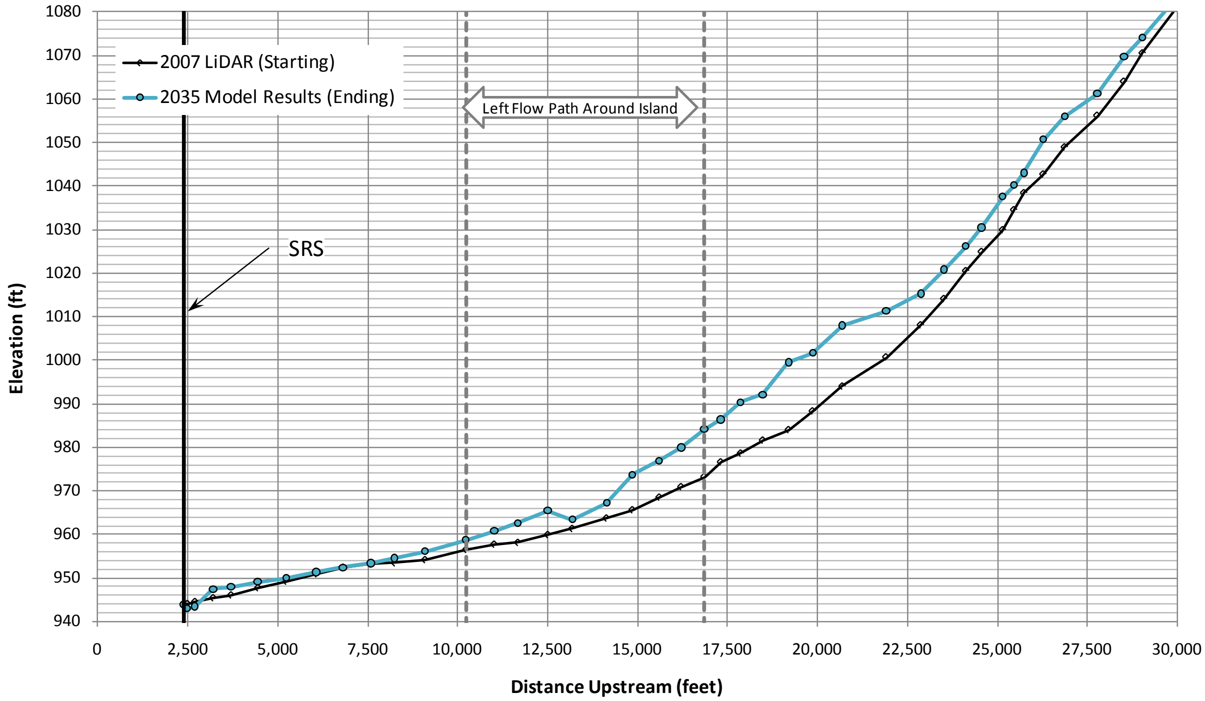

Figure 3.28 Profile of Average Cross-section Elevation for 2007 and 2035, Main Flow Path (around left side of island, see Figure 3.5 for plan view map)

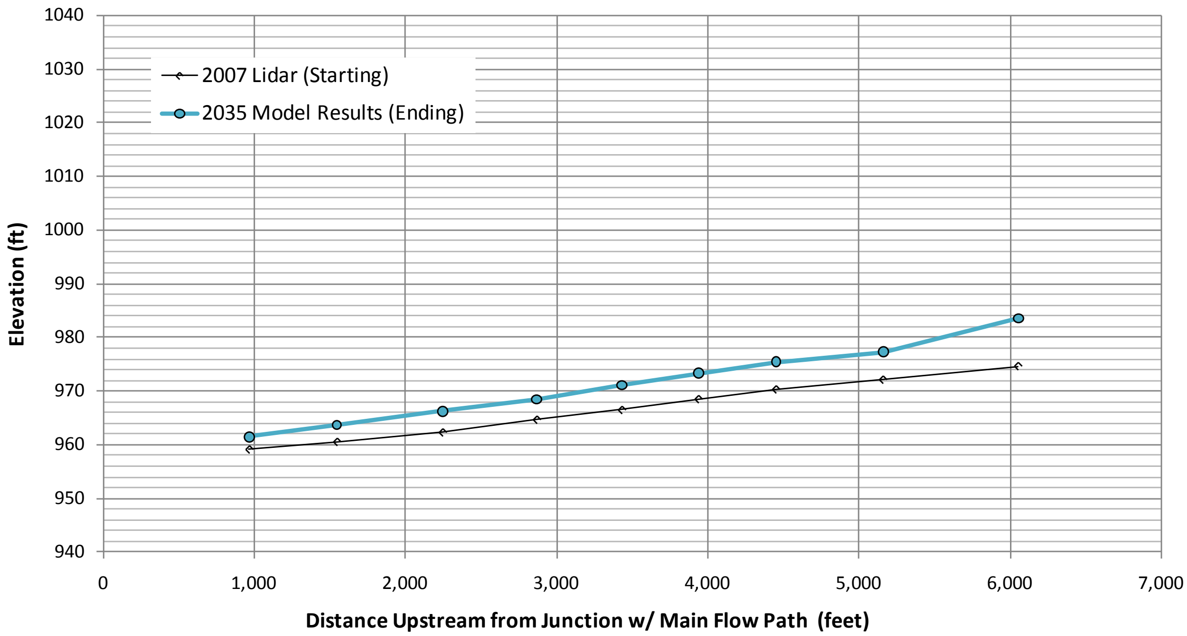

Figure 3.29 Profile of Average Cross-section Elevation for 2007 and 2035, Right Flow Path Around Island (see Figure 3.5 for plan view map)

Results by grain class from the long-term forecast model were also reviewed. A plot of cumulative deposition by grain class over the forecast period is provided in Figure 3.30. Cumulative sediment output from the SRS by grain class through 2035 is shown in Figure 3.31.

Overall trapping efficiency, computed using cumulative values of input and output, is shown graphically in Figure 3.32. Annual trap efficiency is highly variable; however, the cumulative trap efficiency shows a declining trend. The overall trapping efficiency above the SRS over the 28-year simulation was computed to be 25%. The trapping efficiency computed by the Sediment Budget between 1999 and 2007 was estimated to be 37%.

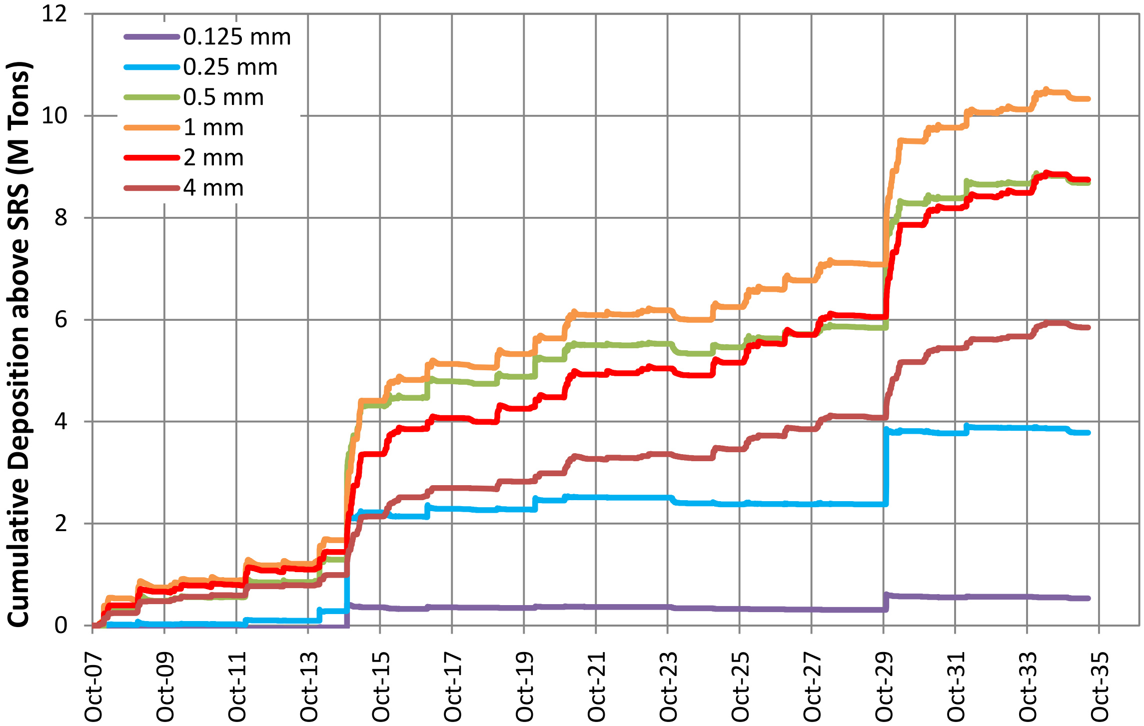

Figure 3.30 Cumulative Deposition by Grain Size above the SRS through 2035

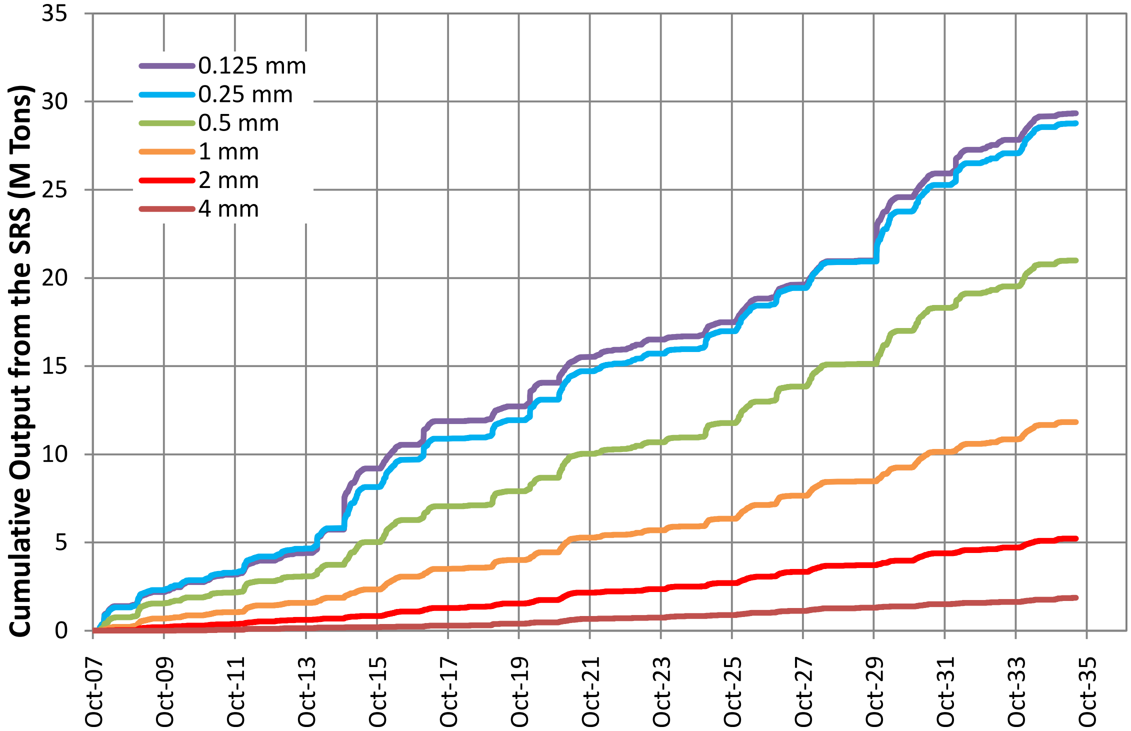

Figure 3.31 Cumulative Sediment Output from the SRS by Grain Size through 2035

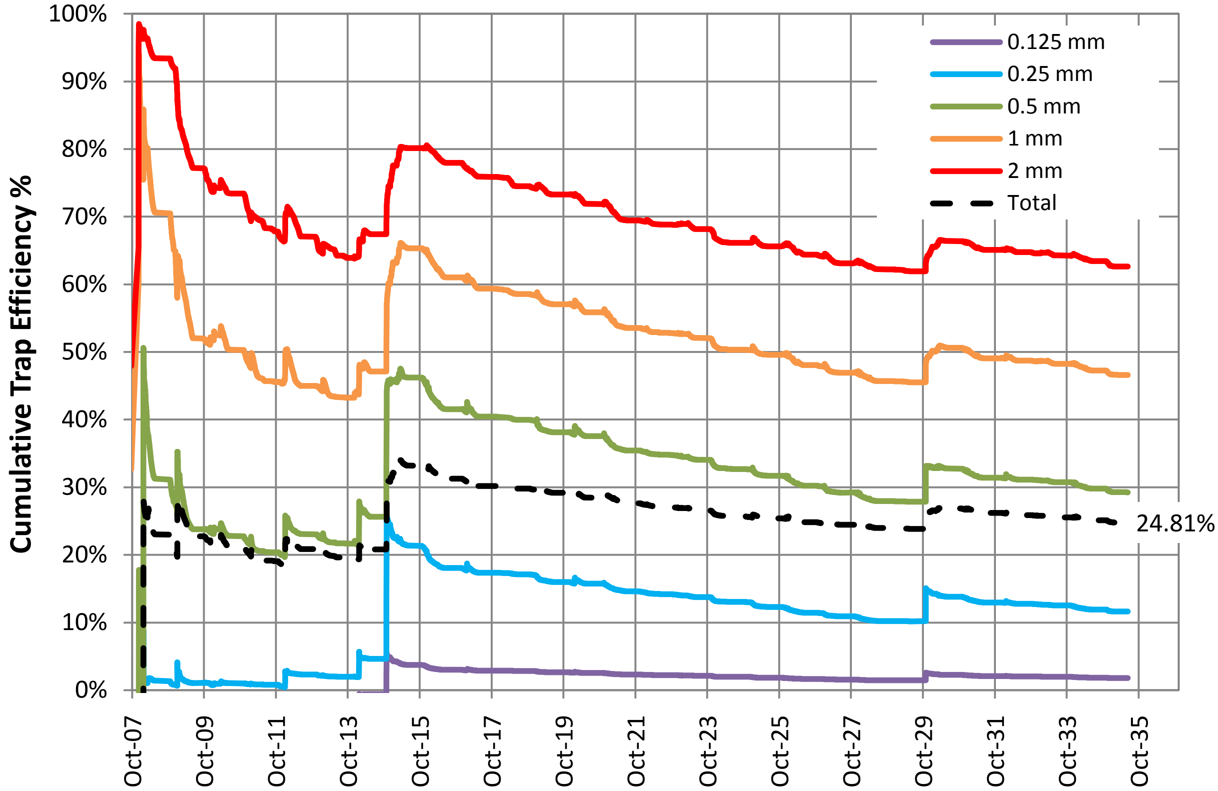

Figure 3.32 Cumulative Trap Efficiency by Grain Class through 2035

The total input, deposition, and output computed by the 1-D model through 2035 for each grain class is shown graphically in Figure 3.33. Table 3.2 provides an overall breakdown of the type of sediment flowing into, depositing, and flowing out of the sediment plain.

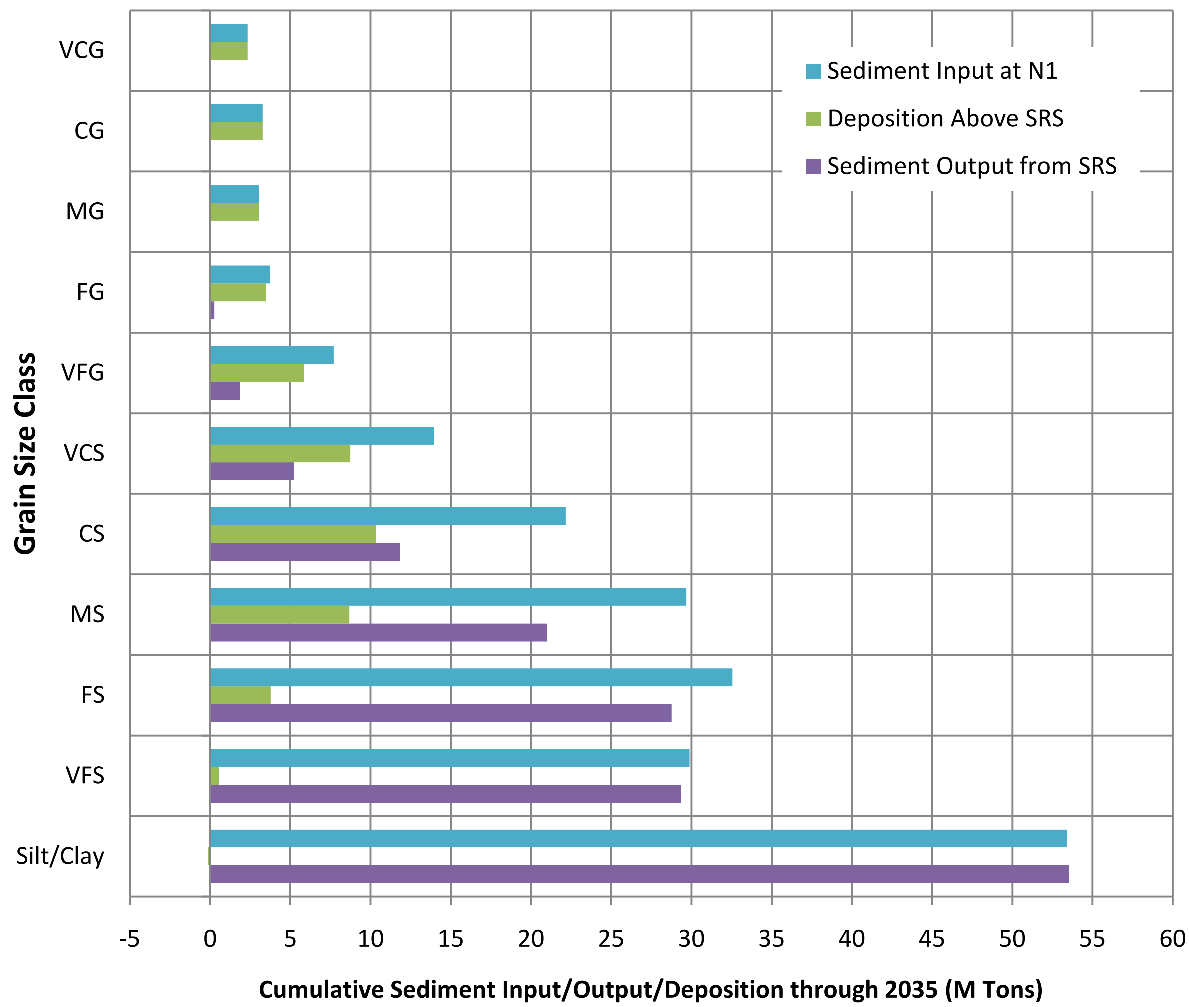

Figure 3.33 Cumulative Sediment Input, Output, and Deposition by Grain Size through 2035

Table 3.2 Percentage of Silt, Sand, and Gravel of Flow Input, Deposition, and Output through 2035

	Input at N1	Deposition	Output from the SRS
Silt/Clay	26%	0%	36%
Sands	64%	64%	63%
Gravel	10%	36%	1%

3.3 2-D MIKE 21C Model

3.3.1 2-D Modeling Approach

The numerical model MIKE 21C (DHI software) was used for the 2-D simulations. MIKE 21C is a depth-averaged Computational Fluid Dynamics (CFD) model well-suited to modeling water and sediment transport through sand-bed rivers. The hydrodynamic module simulates water surface level and lateral and longitudinal velocity variations in response to a variety of forcing functions including: incoming flow volume from the Toutle River upstream, Hoffstadt Creek, and three other northern tributaries as well as two from the south; bottom shear stress; and other possible influences including wind shear, barometric pressure, Coriolis acceleration, momentum dispersion, sources and sinks, evaporation, flooding and drying, and wave radiation stresses. Since the point of this study was to evaluate change in bed geometry within the sediment deposition plain and the amount of sediment retained within and conveyed beyond the SRS over long periods of time; wind shear, barometric pressure variation, evaporation, and wave radiation stresses were omitted.

3.3.2 Model Development

3.3.2.1 Model grid

MIKE 21C operates exclusively in SI units and is based on a curvilinear grid. A curvilinear grid is similar to a structured grid in that each cell has four sides, however, the cells can be non-orthogonal – allowing them to follow irregular river channel alignments. The grid for the Toutle River above the SRS study includes the lower 6.5 mile river section varying between approximately 0.5 and 0.75 miles in width. The roughly 6,900 cell grid (164 cells in the flow direction x 42 cells in the cross-stream direction) representing this area is shown in Figure 3.34. Grid resolution varies spatially but is roughly 20 m x 30 m (cells are generally longer in the direction of flow).

Run times for the 2003 to 2006 calibration period take 6 to 8 hours even though a portion of the cells above modeled discharge levels was computationally disabled. Approximately 800 cells (11% of the entire grid) representing the overbanks and two major southern islands were disabled by assigning them a high elevation (616 m) to designate them as land during all flow levels. These cells are colored red in Figure 3.35. The cell centered grid elevations ranging from 943.9 ft (287.7 m) above sea level at the SRS spillway to over 1,230 ft (375 m) upstream of N1 are shown as well in Figure 3.35.

Roughness in the model from Manning's n = 0.035 for sand to n = 0.043 for backwater areas south of the main island and n = 0.060 for heavily vegetated bank and island areas. Figure 3.36 shows the model roughness distribution where yellow cells have n = 0.035, green cells have n = 0.043, and blue cells (heaviest vegetation) have n = 0.060.

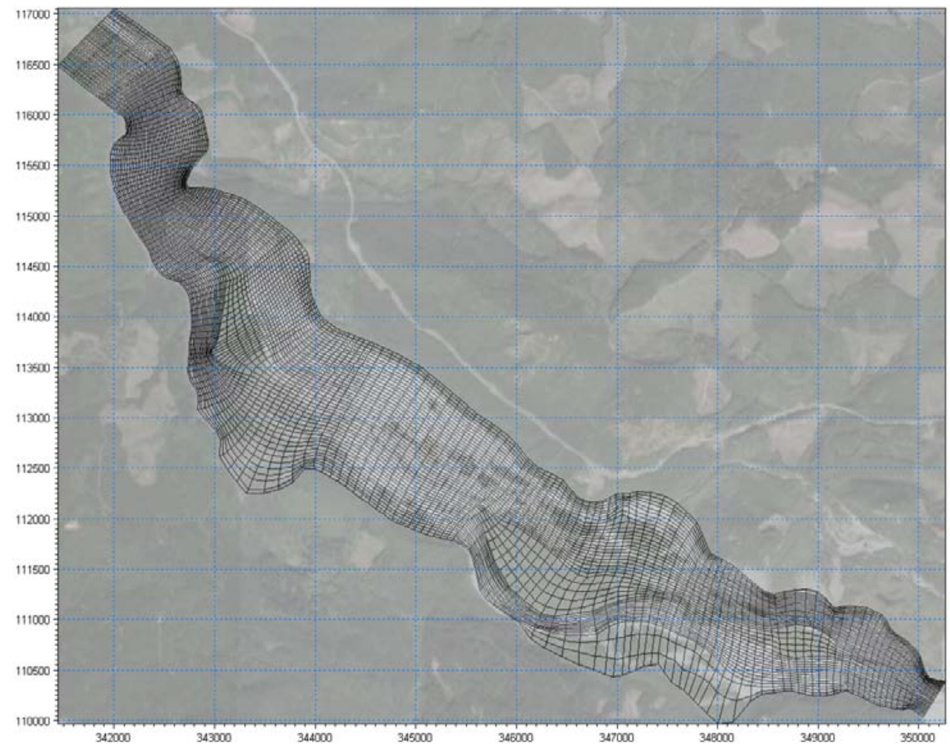

Figure 3.34 Toutle River above the SRS Model MIKE 21C Mesh

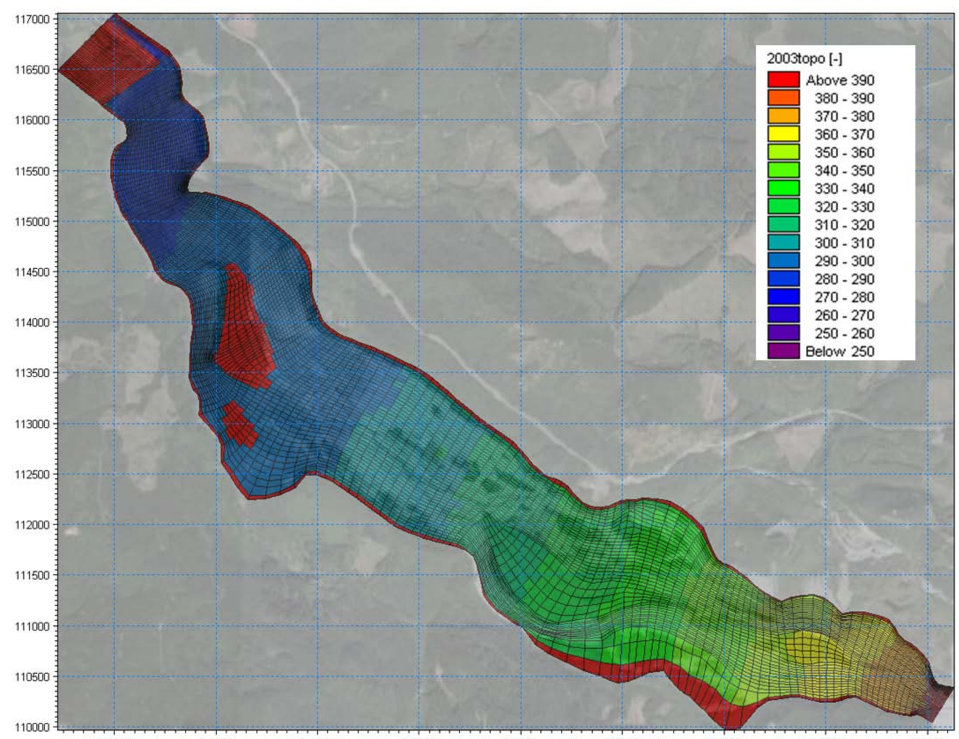

Figure 3.35 Toutle River above the SRS 2003 Bathymetry (MIKE 21C color-coded elevations are in meters)

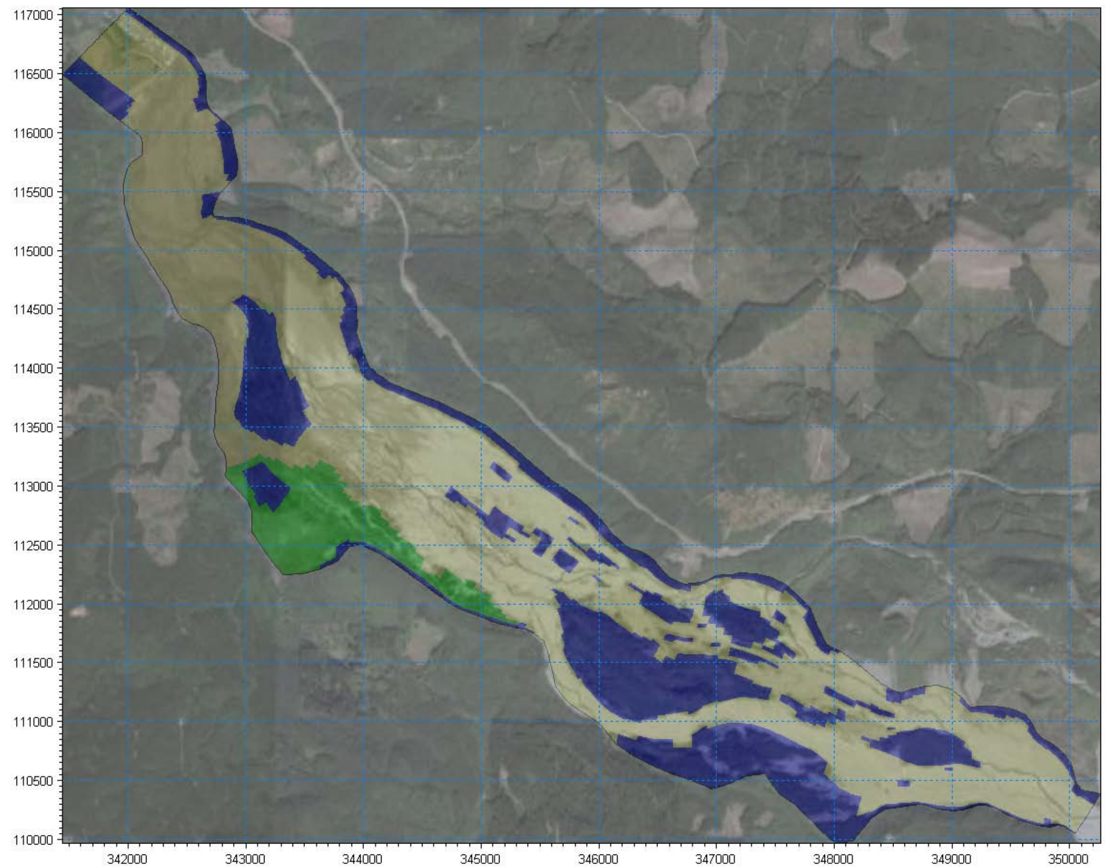

Figure 3.36 Model Reach Roughness Variation (yellow *n* = 0.035, green *n* = 0.043, blue *n* = 0.060)

3.3.2.2 Topography

Three sets of surface data were used to build the calibration surfaces (2003 and 2006) and the long-term Toutle River model surface (2007). All surveys were originally provided in feet (Washington South State Plane Coordinate System, North American Datum of 1983 (NAD83) horizontal, and North American Vertical Datum of 1988 (NAVD88) datums). Since MIKE 21C operates in meters only, the surface generated from the survey points was converted to meters.

The 2003 survey was conducted in Oct of 2003. The 2006 survey was performed by Watershed Sciences and submitted to the USACE on Nov 16, 2006. Data were collected Oct 21, 2006. The 2007 LiDAR survey has a 10-ft x 10-ft grid, data for this survey were collected between Oct 22 to 27, 2007.

3.3.2.3 Sediment

Two kinds of sediment information are necessary for input into the hydrodynamic sediment transport model: 1) bed material gradation and 2) inflowing sediment gradation.

Since the majority of the sediment filling in the SRS is coming from upstream of N1, the model bed material was selected as an average of the Elk Rock and SRS 5 samples shown in Figure 3.37. Some scour is expected in the upper reaches of the model where the bed material will be well represented by this gradation (Table 3.3). The lower reaches of the model are depositional and will become covered with incoming sediment as the model is initiated.

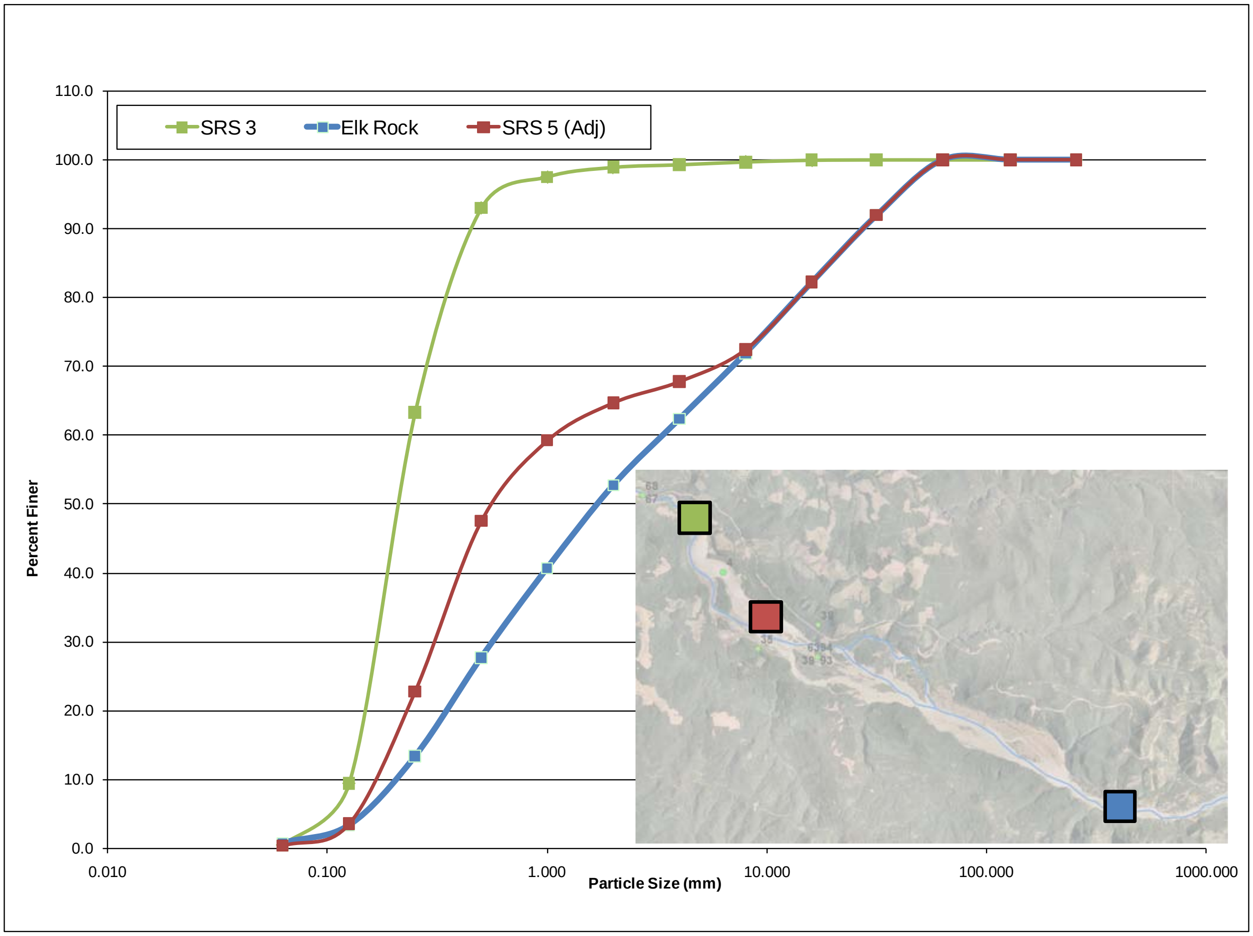

Figure 3.37 Toutle River Bed Material Gradation Curves – Samples (2010 SBR)

Table 3.3 Model Bed Material Gradation by Size Class

Size Class (mm)	Percent in Size Class (%)
0.0125	10
0.25	15
0.5	15
1.0	10
2.0	10
4.0	40

The inflowing sediment for the calibration period of WYs 2004 through 2006 is based on a concurrent sediment budget study. The sediment inflow curve in cubic meters per second (cms) relative to the daily average discharge of the Toutle River below the SRS is shown in Figure 3.38. MIKE 21C allows an input hydrograph containing sediment by size class. For the WY 2004 through WY 2006 calibration run, this is shown in Figure 3.39.

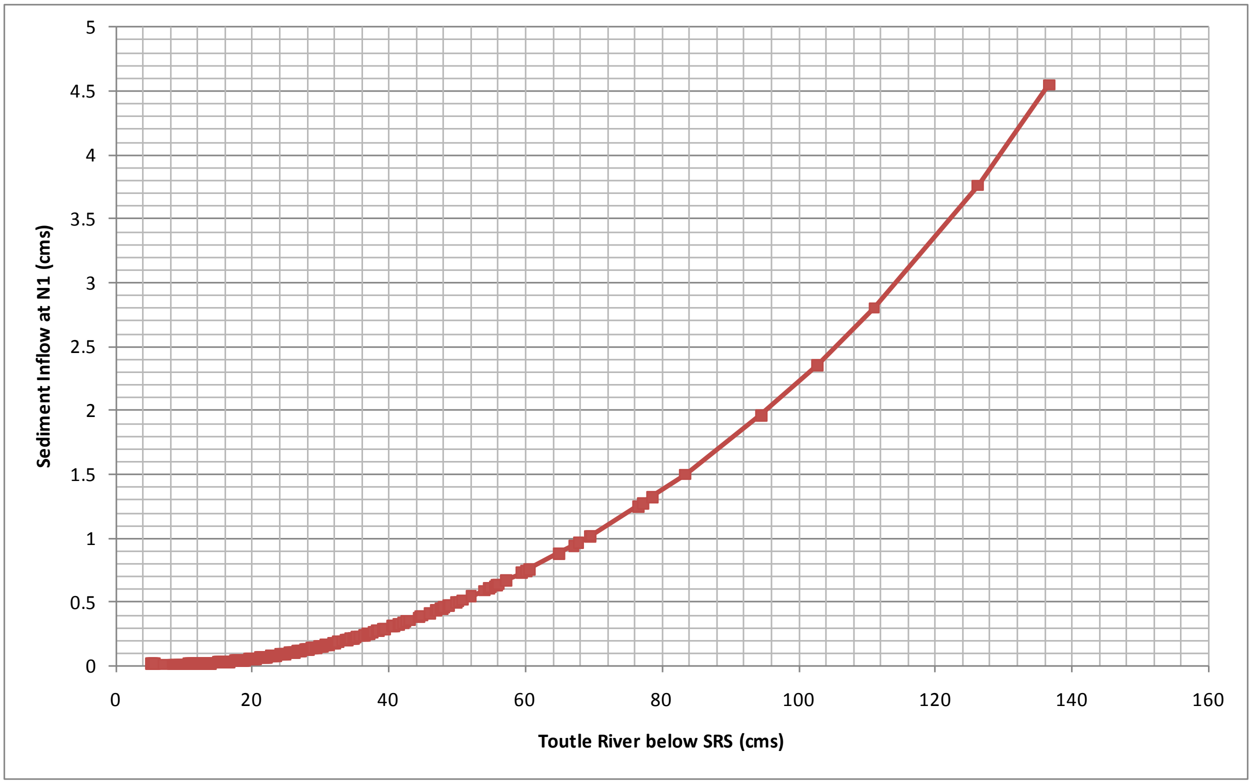

Figure 3.38 Sediment Inflow Rating Curve

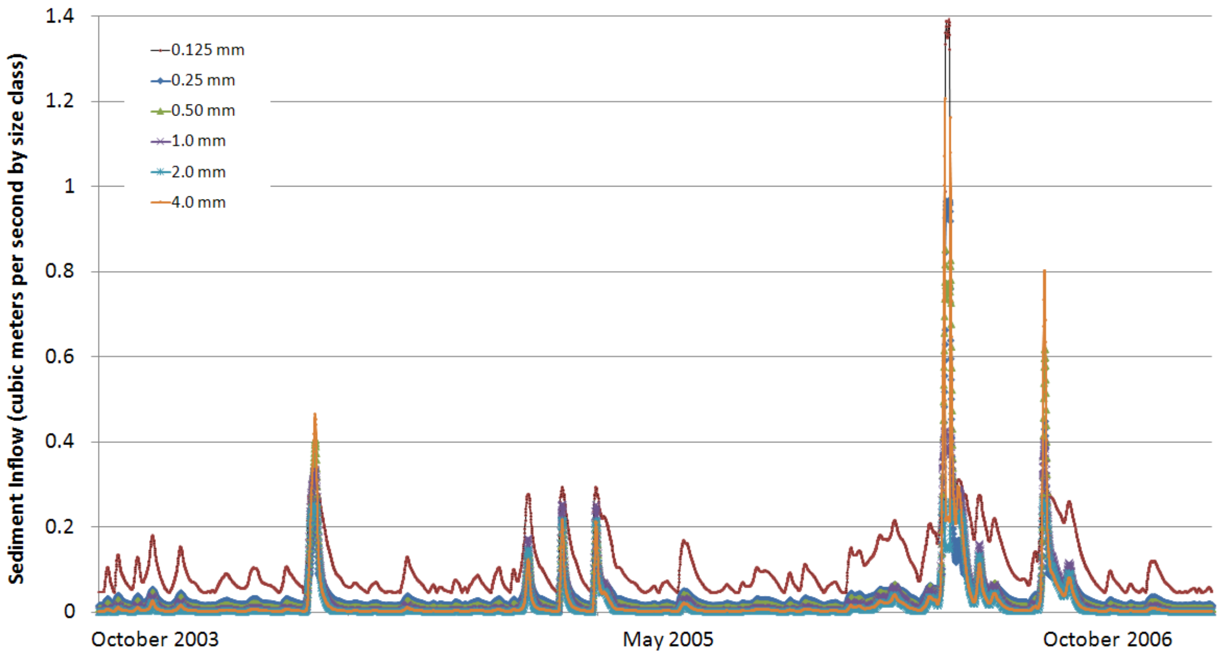

Figure 3.39 Sediment Inflow (cubic meters per second by size class) – Calibration Run

The 28-year projected sediment inflow curve has temporally varied sediment input for a series of low, normal, and high inflowing sediment years. Figure 3.40 shows the sediment inflow hydrograph for the 28-year FEDS projected sedimentation study.

The gradation of inflowing sediment is adjusted to reflect sediment concentration variability by size fraction for different discharges. The sediment gradation per inflowing sediment volume in tons per day is shown in Figure 3.42**.** The sediment gradation curves of the samples in Figure 3.37 are duplicated in Figure 3.41 (bold blue, red, and green lines) along with the model bed material (dotted line). The coarsening of inflowing sediment can be observed as the total tons per day of incoming sediment increases.

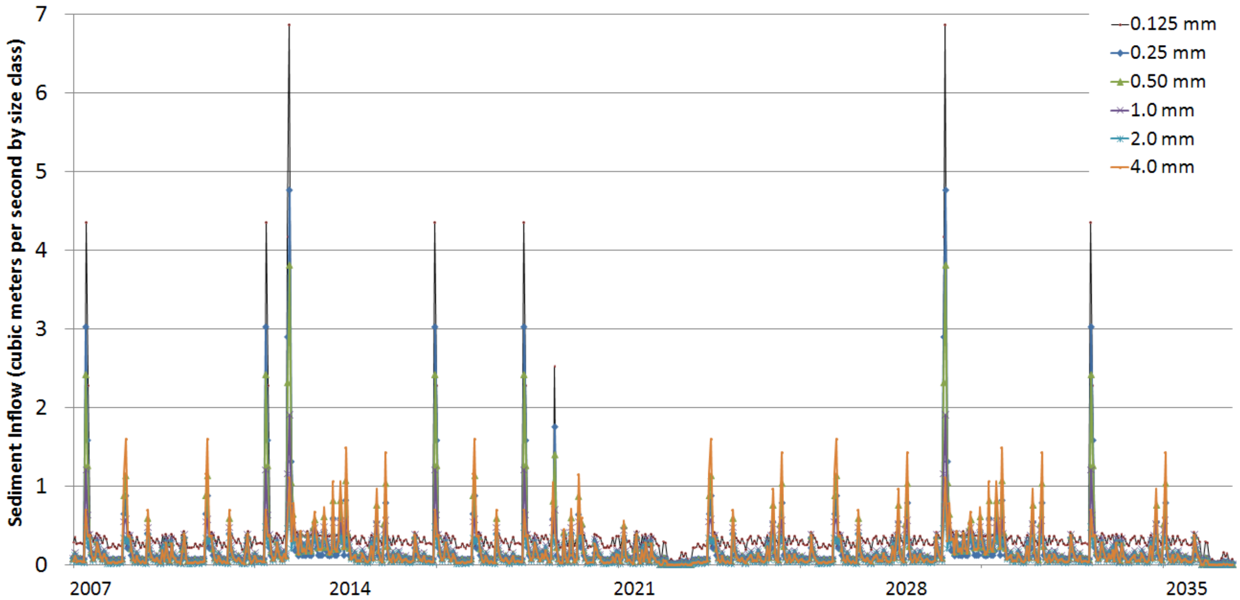

Figure 3.40 Sediment Inflow (cubic meters per second by size class) – 28-year FEDS Run

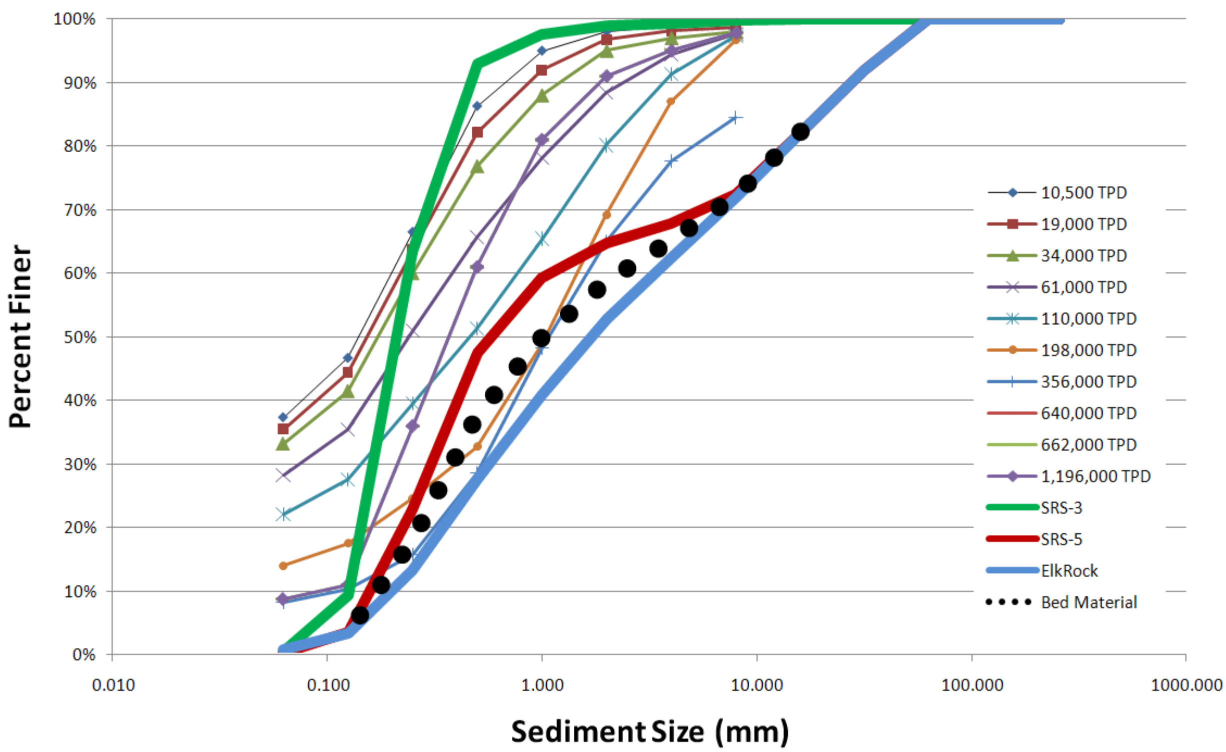

Figure 3.41 Sediment Gradation Curves for Inflowing Sediment (grain size in millimeters and percent passing for inflows ranging from 10,500 tons per day to 1.2 M Tons per day)

3.3.2.4 Model boundary definitions

For a typical MIKE 21C 2-D model, at each model boundary either a water surface elevation or a flow is specified. All models must include at least one boundary where water surface elevation is defined and one boundary where flow is given. The remaining boundaries can specify water level or flow. This model has seven model boundaries: 1) the starting water surface elevation in the model is defined at the SRS (Row 164), 2) incoming flow from the upstream watershed and Tributary N1 is entered into the very upstream row of the model (Row 0), 3) Tributary N2 enters as a flow source at Row 40, 4) N2 comes in at Row 136, 5) N3 at Row 152, 6) S1 at Row 50, and 7) S2 at Row 85 (see Figure 2.5 and Table 2.10 for tributary drainage area and location).

Each of the tributary inflows is determined by multiplying flow at the SRS by the ratio of their individual areas to the total tributary watershed area. Figure 3.42 shows incoming flow per tributary for the 3-year calibration period and Figure 3.43 shows the same for the 28-year FEDS projection run. The water surface elevation boundary at the SRS was determined by creating a critical flow condition at the SRS within the model and verifying the model generated water surface elevations with a series of manually-calculated water surface elevations using the weir equation. Figure 3.44 shows the relationship between MIKE 21C computed water surface at the SRS and the calculated water surface using the weir equation.

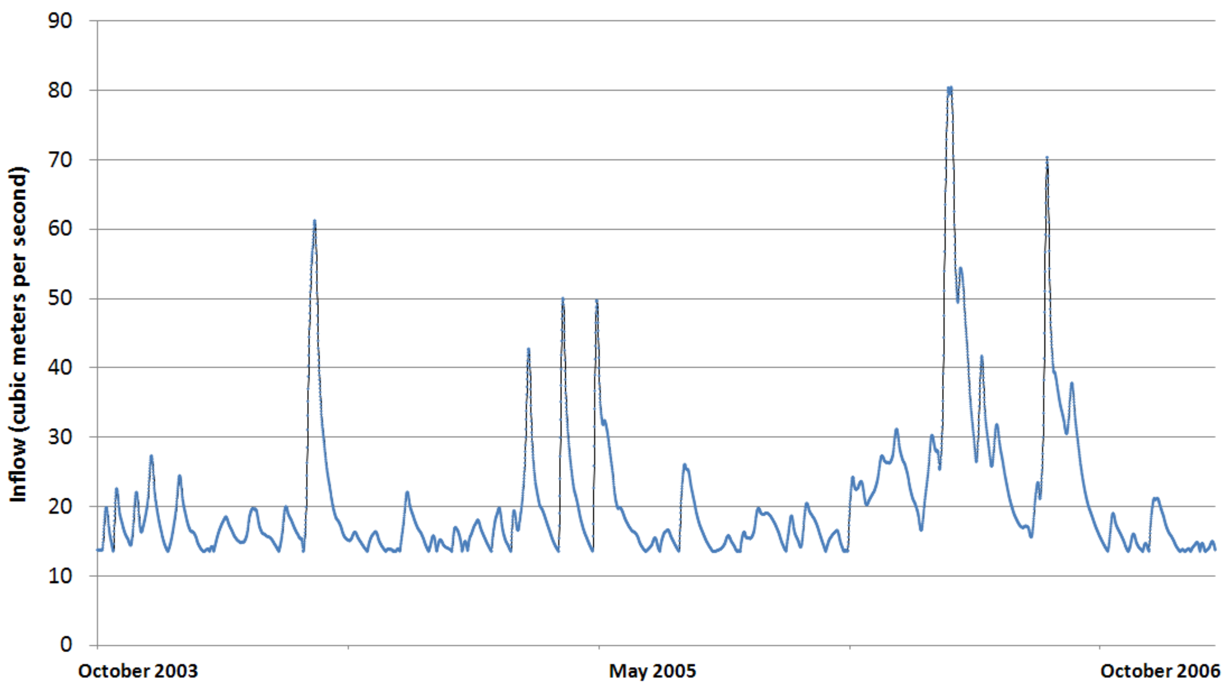

Figure 3.42 Upstream Inflow Hydrograph for the 3-year Calibration Run (cubic meters per second vs. time)

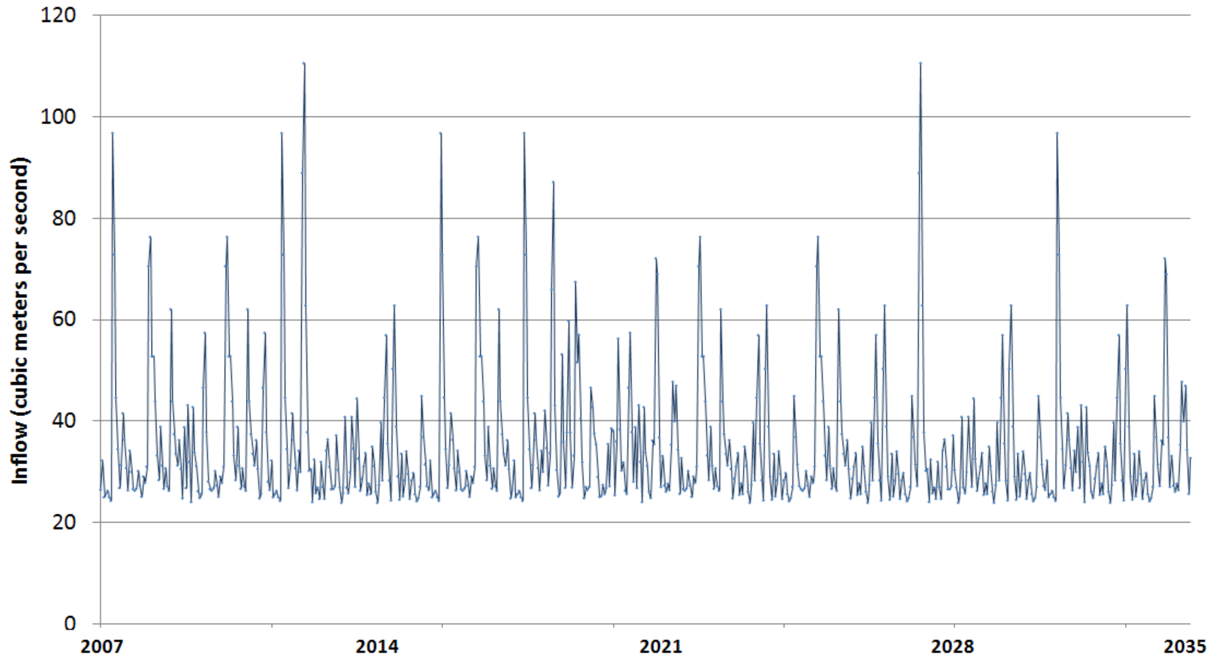

Figure 3.43 Upstream Inflow Hydrograph for the 28-year FEDS Projection Run (cubic meters per second vs. time)

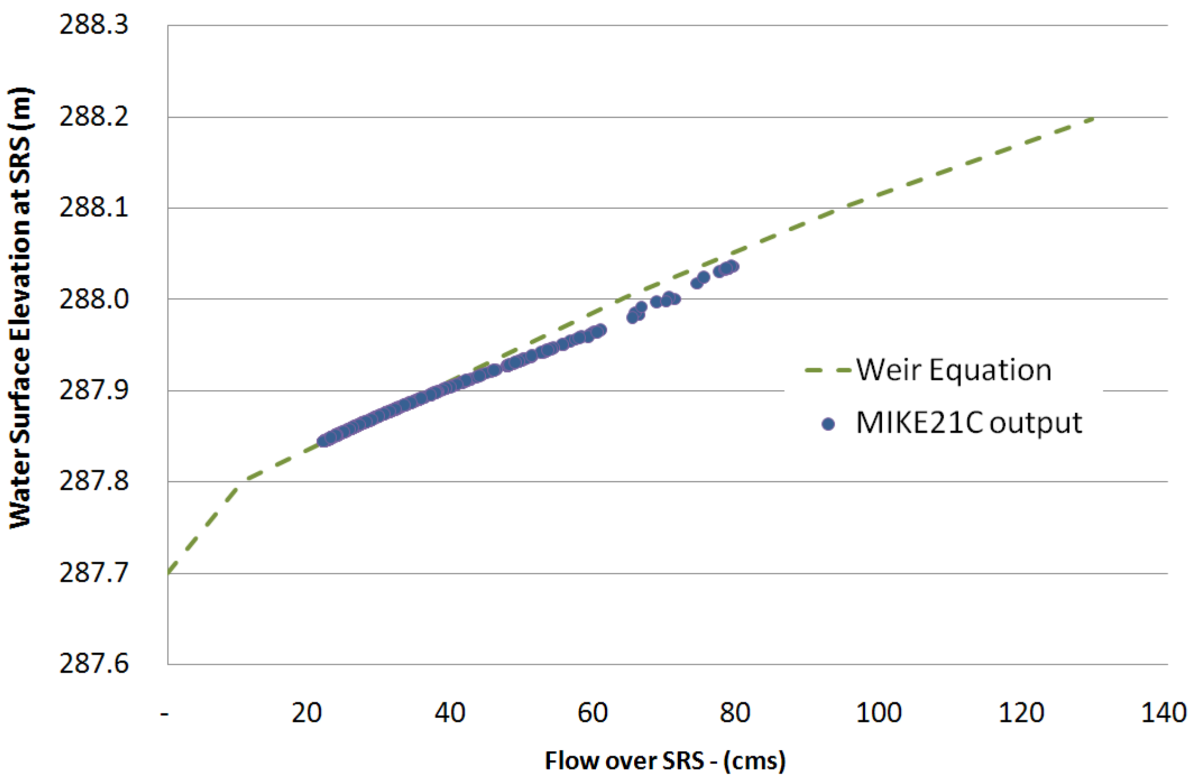

Figure 3.44 Comparison of MIKE 21C Downstream Computed Water Surface Elevation vs. Manually-computed Values

3.3.2.5 Model time series simplification

For the calibration run, the 3 years of inflow were reduced to minimize run times. Over 26,300 hours of inflow data (sediment and water) were reduced to 5,300 hours by eliminating flows less than 850 cfs at the SRS. This simplifying assumption reduced run time by 80% but retained over 70% of the inflowing sediment load. Each hourly sediment inflow value was hyperconcentrated by multiplying by a factor of 1.4 to incorporate the entire sediment inflow hydrograph in only 20% of the time steps. This reduces the processing time required for a 3-year run from 28 hours to 7 hours. Figure 3.45 shows a comparison of the 3-year inflow hydrographs – the full 3 years is in the lower half of the figure, the compressed hydrograph with flow values over 850 cfs at the SRS is shown in the upper half. A similar simplification was made with the 28-year inflow hydrograph. Shortening the 28-year hydrograph from 245,000 hours of data to 15,300 allowed a 54-hour run (representing 8% of the flow days and 60% of the inflowing sediment). The 28-year sediment hydrograph was hyperconcentrated by a factor of 1.7 to incorporate the entire sediment inflow hydrograph in the compressed time period.

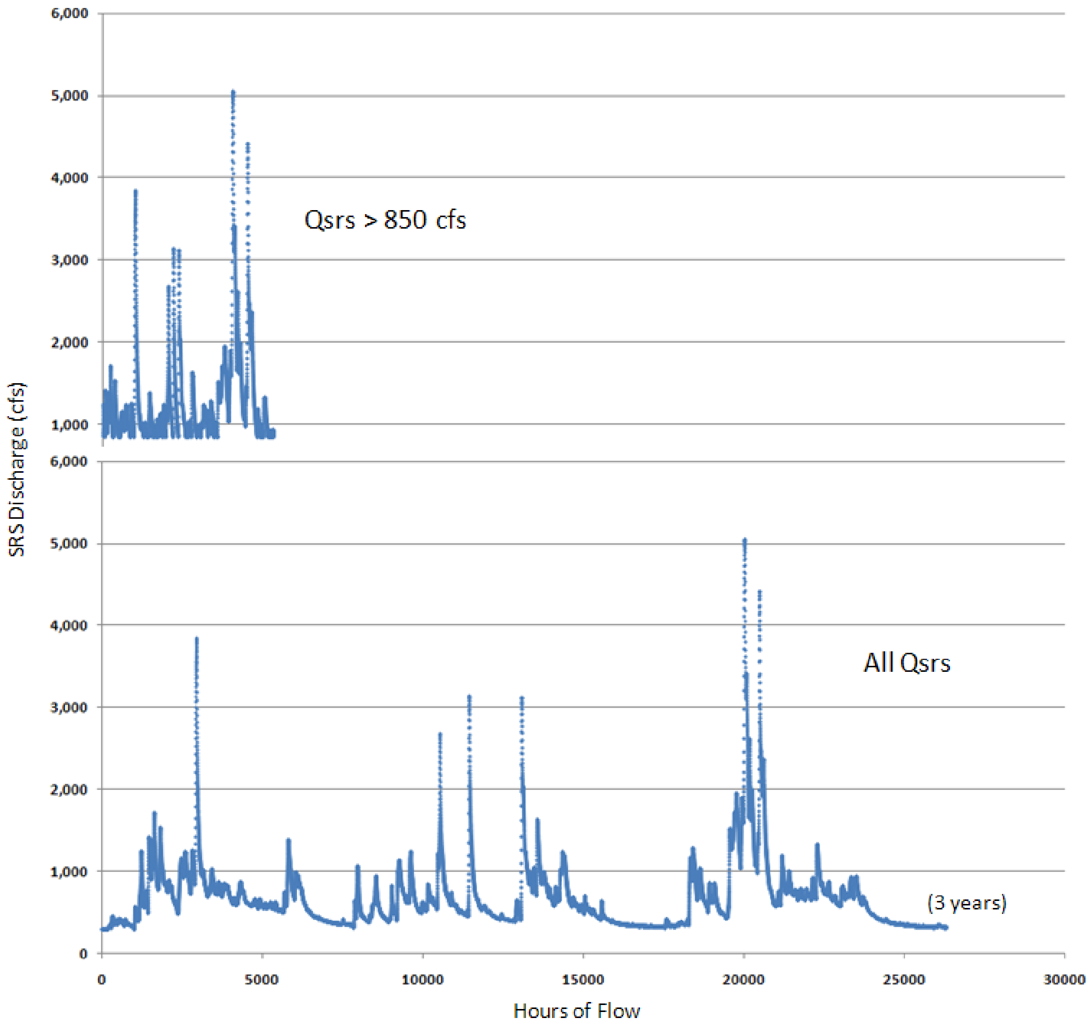

Figure 3.45 Total Inflow – Three Water Years vs. Only Flow above 850 cfs at the SRS Comparison

3.3.2.6 Time step

Model stability is related to time step length and grid cell size. High cell resolution (smaller cells) and high-flow velocities requires the use of smaller time steps. The Toutle River model was found to be stable with a hydraulic time step on the order of 1 second. A 1-second time step keeps the Courant Number (V_C) less than 0.05 when velocities (u) are less than 2 m/second, and cell size (Δx) is about 40 m in the flow direction:

Courant Number: $$V_C = \frac{u \cdot \Delta t}{\Delta x}$$ **Equation 3.2**

The sediment time step was set at 1 minute so that every sixty hydraulic time steps lead to one sediment transport update and bed recalculation.

3.3.2.7 Sediment transport function

The Engelund-Hansen function was selected for this study. This function is based on flume data with sediment sizes between 0.19 and 0.93 mm and has been extensively tested and found to be consistent with field data for sandy rivers with substantial suspended load. The Engelund-Hansen function was developed based on flume research, but has been historically applied to sediment transport problems outside the developmental range.

The general form of the transport equation function is:

Engelund-Hansen: $$g_s = 0.05\gamma_s V^2 \sqrt{\frac{d_{50}}{g\left(\frac{\gamma_s}{\gamma} - 1\right)}} \left[\frac{\tau_o}{(\gamma_s - \gamma) d_{50}}\right]^{3/2}$$ **Equation 3.3**

where,

g_s = unit sediment transport;
γ_s = unit weight of solid particles;
V = average channel velocity;
d_{50} = particle size of which 50% is smaller;
g = gravitation coefficient;
γ = unit weight of water; and
τ_o = bed level shear stress.

3.3.3 Calibration

Many topographic surveys are available for the study reach. However, the quality of LiDAR surfaces representing the study area in 2003 and 2006 along with the available hydrologic record and sediment data resulted in this period being selected for model calibration purposes.

The inflow hydrograph was limited to 20% of the days in the 3-year period to minimize run times (as discussed in Model Time Series Simplification (Section 3.3.2.5)). The flow range modeled in the calibration run varied from 24 to 143 cms (850 to 5,050 cfs) at the SRS. By applying the inflow and sediment inflow input files to the 2-D model, output was generated that allows for verification of this approach. Figure 3.46 shows the results of the 2003 to 2006 model runs in terms of local scour and deposition. The upstream portion of the model (from Row 0 to about Row 70) is the steepest portion of the model and is characterized by confined channels that tend to scour over the period of this run. Below Row 70 and down to the SRS (Row 160) the sediment plain was shown to be depositional.

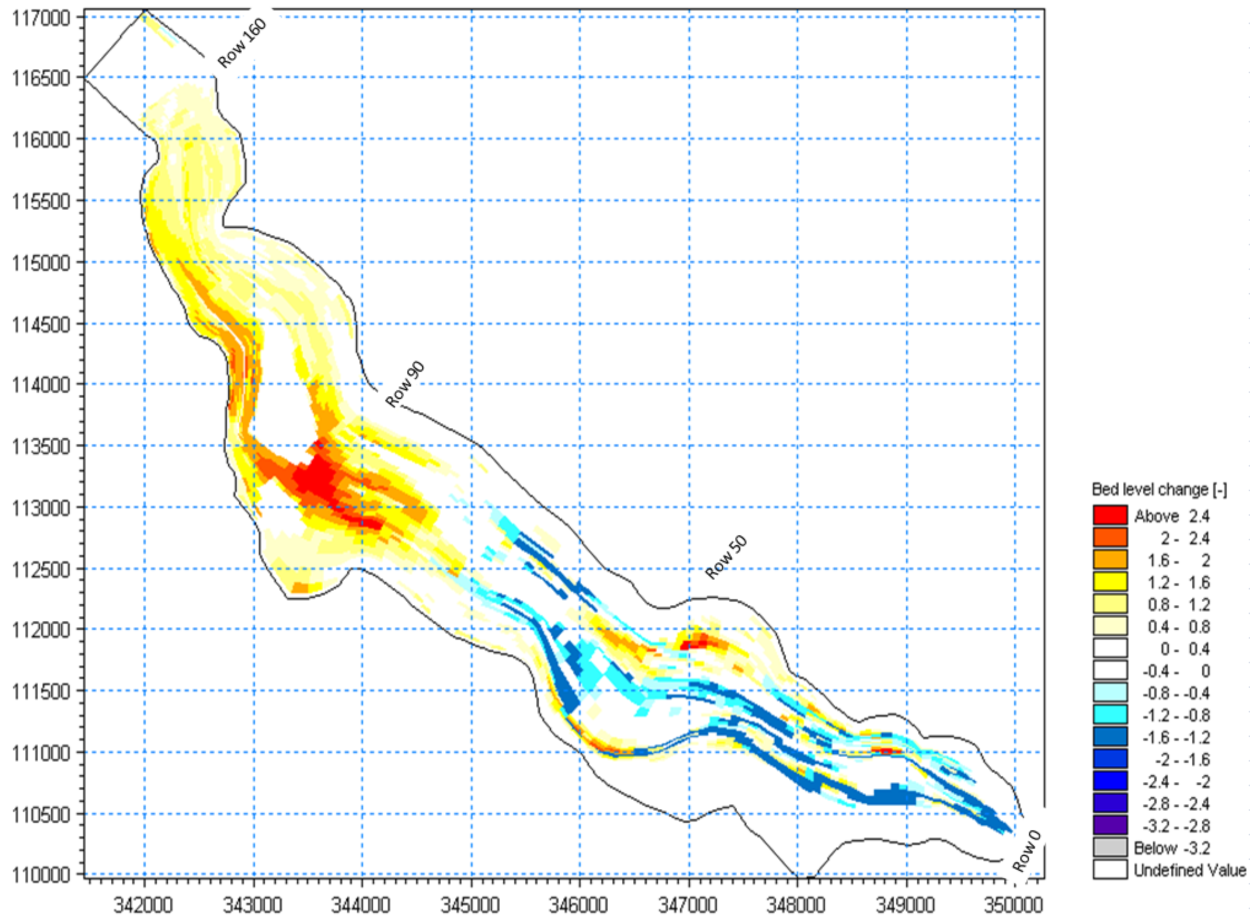

Figure 3.46 2003 to 2006 Model Calibration – Bed Level Change (sediment deposition and scour) (units in meters)

Figure 3.47 shows a comparison of the scour and deposition trends generated from the 2-D model vs. the difference between the 2006 and 2003 LiDAR surveys. If we consider channel bed level change in terms of accumulated volume from upstream to downstream, the model is in good agreement with the observed changes in topography between LiDAR surveys.

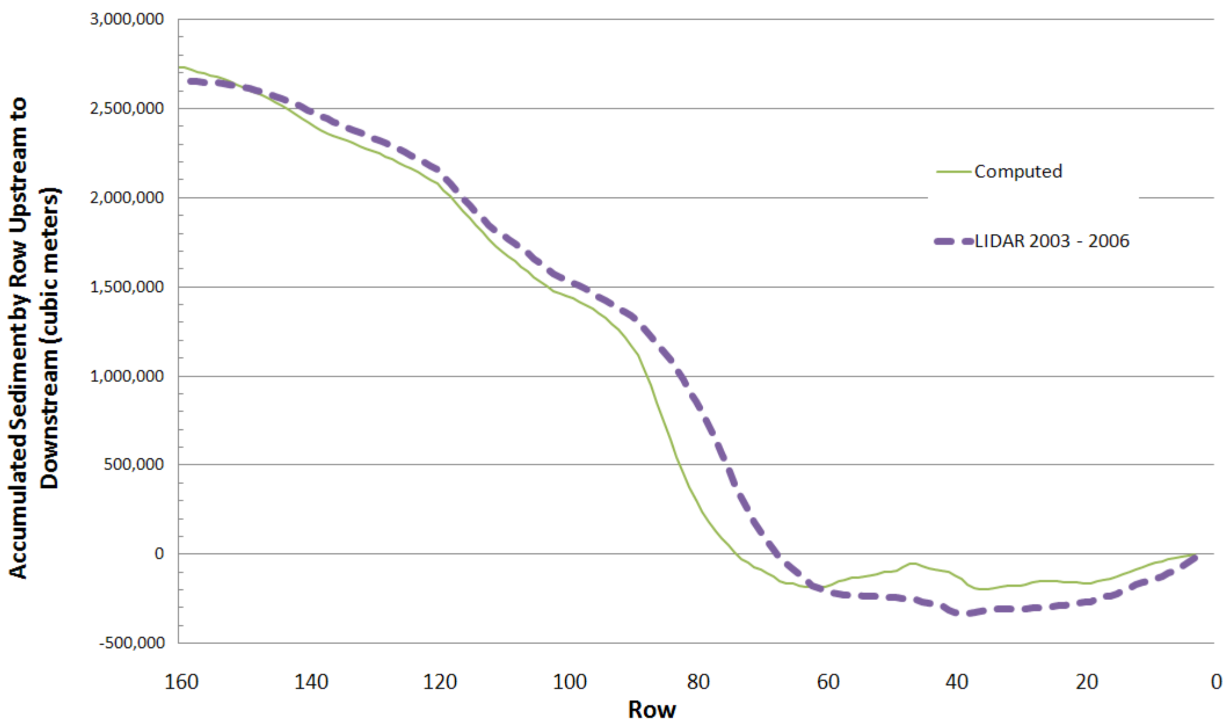

Figure 3.47 2003 to 2006 Model Calibration – Sediment Deposition from Upstream to Downstream

A goal of this study was to facilitate understanding of the existing and projected trapping efficiency of the SRS and to quantify (by size class) the amount of sediment that is currently passing and is expected to pass the SRS over time. Figure 3.48 and Figure 3.49 show the SRS trapping efficiency and cumulative tons of sediment passing the SRS for the 2003 to 2006 calibration model run, respectively.

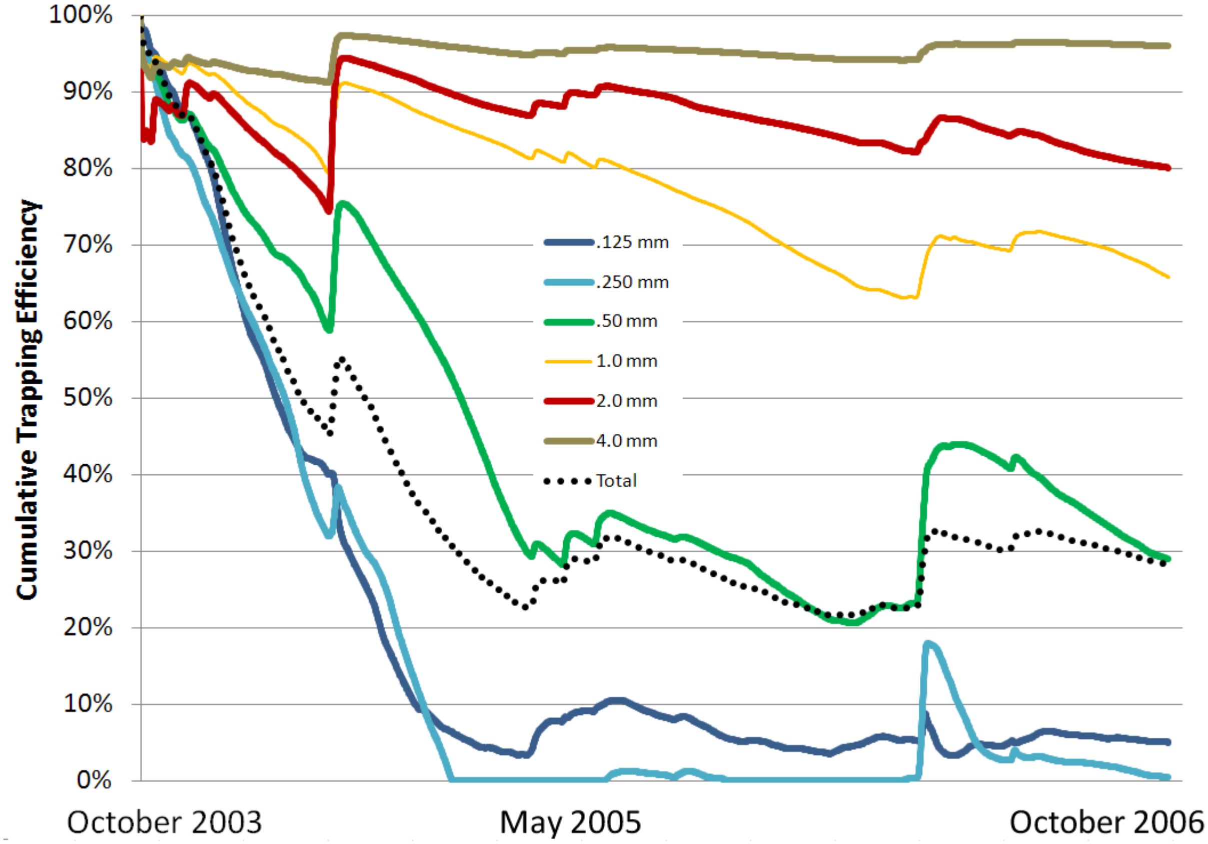

Figure 3.48 2003 to 2006 Model Calibration – SRS Cumulative Trapping Efficiency by Grain Size

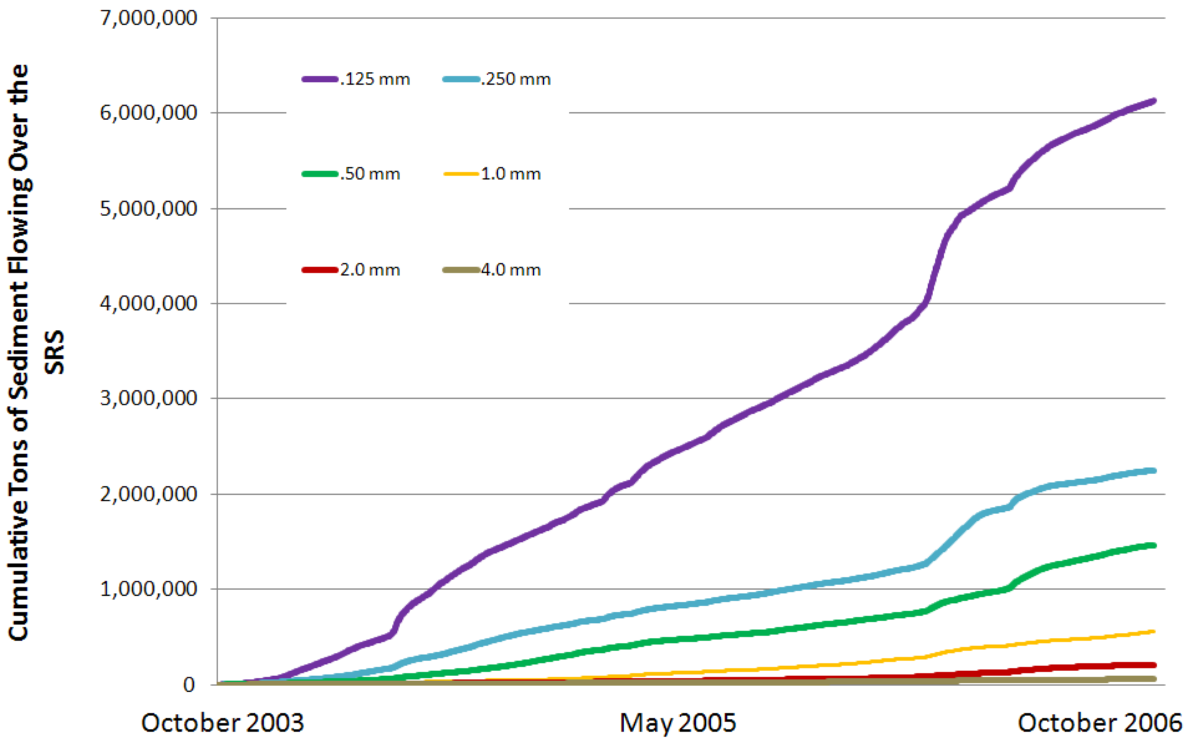

Figure 3.49 2003 to 2006 Model Calibration – Cumulative Tons of Sediment Flowing over the SRS

Results of the 2-D model indicate that at this time (post 2006) the SRS is about 30% efficient at trapping incoming sediment. Larger sediment in the 1.0- to 4.0-mm classes is primarily retained by the SRS at present (65 to 95%), and finer materials are allowed to pass over the SRS (most of the 0.125- and 0.250-mm material and about 70% of the 0.50-mm material is passing the SRS at present).

Of the over 14 M Tons of sediment entering the calibration period model, about 10 M Tons of finer material (0.125 to 0.50 mm) and almost 1 M Tons of coarser sediment (larger than 0.50 mm) passed over the SRS.

3.3.4 Long-term Forecasting Results

Low flows were also removed from the 28-year FEDS run as described in the Model Time Series Simplification section. The range of flows modeled for the FEDS run was 42 to 197 cms (1,500 to 6,500 cfs) at the SRS. Reducing the amount of low-flow days modeled allowed for a reasonable model run time on the order of 2 days (instead of 2 to 3 weeks).

Figure 3.50 shows the predicted deposition pattern after the 28-year FEDS run. The entire model domain is depositional except for a few concentrated upstream flow channels delivering water and sediment to the sediment plain. Large amounts of sediment are deposited upstream from the island series (Row 90 to about Row 60).

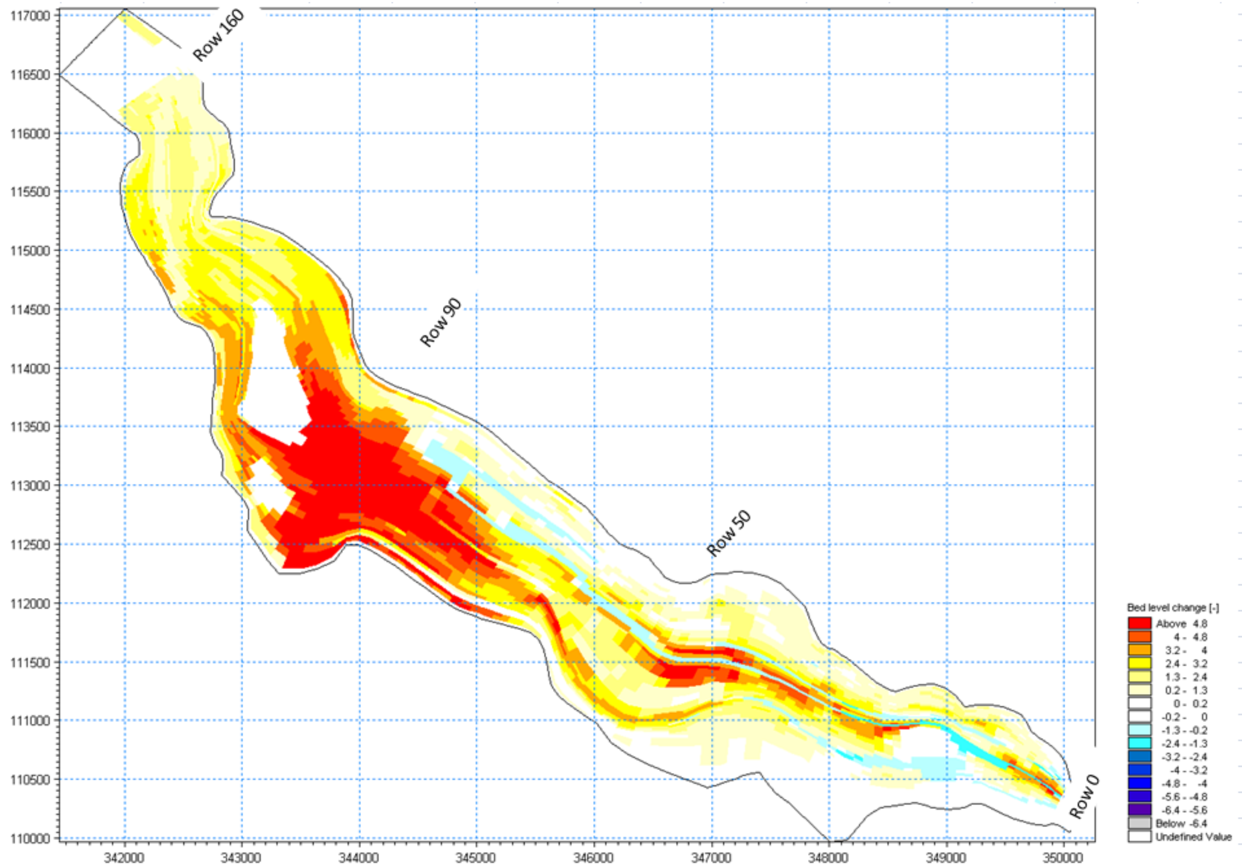

Figure 3.50 28-year FEDS Run – Bed Level Change (sediment deposition and scour) (units in meters)

Comparing the trapping efficiency at the end of the 28-year FEDS run (Figure 3.51) to the present trapping efficiency (Oct 2006 from Figure 3.48), it is clear that by 2035 the SRS trapping efficiency of all sizes of material is expected to decrease. Larger material (4 mm) will increasingly pass over the SRS; about 20% is expected to pass in 2035 as compared to about 5% passes currently. One- and two-millimeter sediment shows dramatic decreases in trapping SRS efficiency from about 70 to 80% now to 30 to 20% trapping efficiency in 2035. Almost all of the finer material is expected to pass over the SRS in 2035, and total trapping efficiency drops from about 30% now to about 20% at the end of the FEDS simulation.

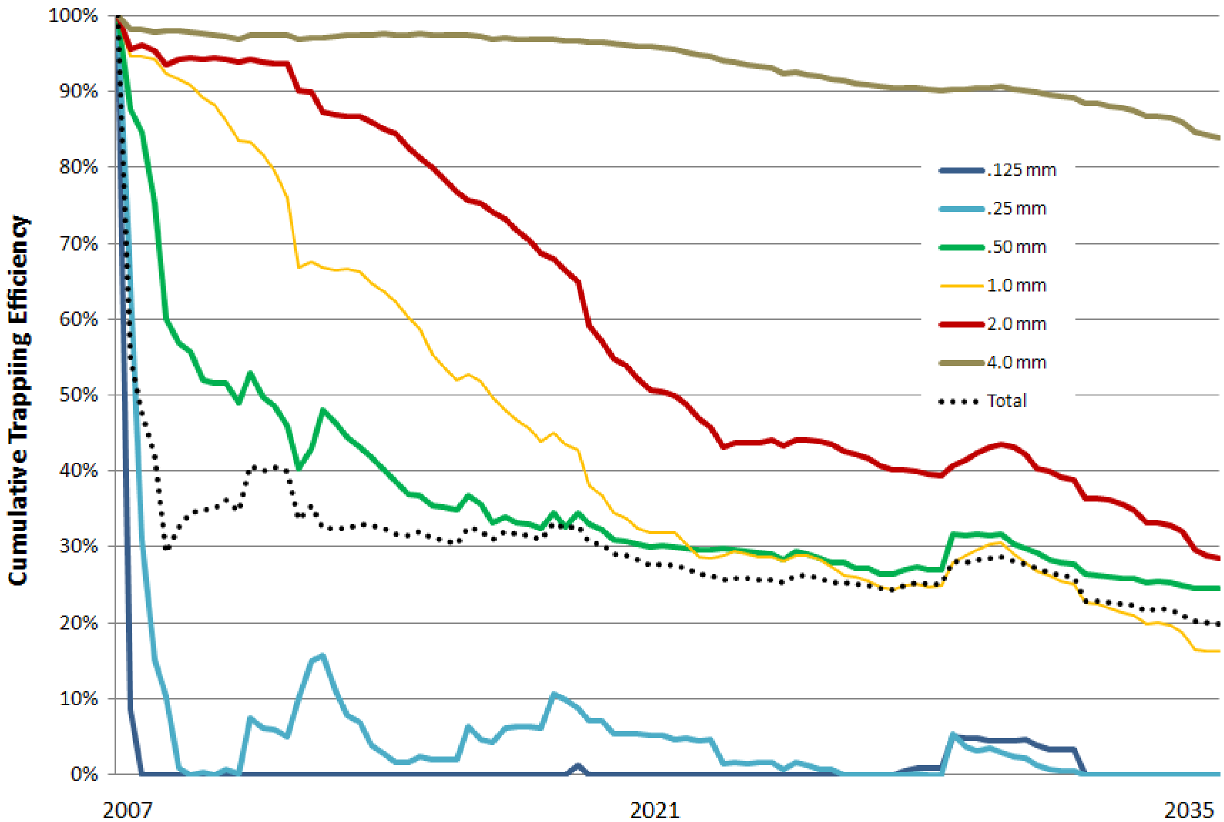

Figure 3.51 28-year FEDS Run – SRS Cumulative Trapping Efficiency by Grain Size

Of the over 215 M Tons of sediment entering the system over the 28-year FEDS model, more than 126 M Tons of finer material (0.125 to 0.50 mm) and over 45 M Tons of coarser sediment (larger than 0.50 mm) are projected to pass over the SRS (80% of inflowing sediment is conveyed over the SRS). Figure 3.52 shows the cumulative tonnage of sediment expected to pass over the SRS throughout the long-term forecast.

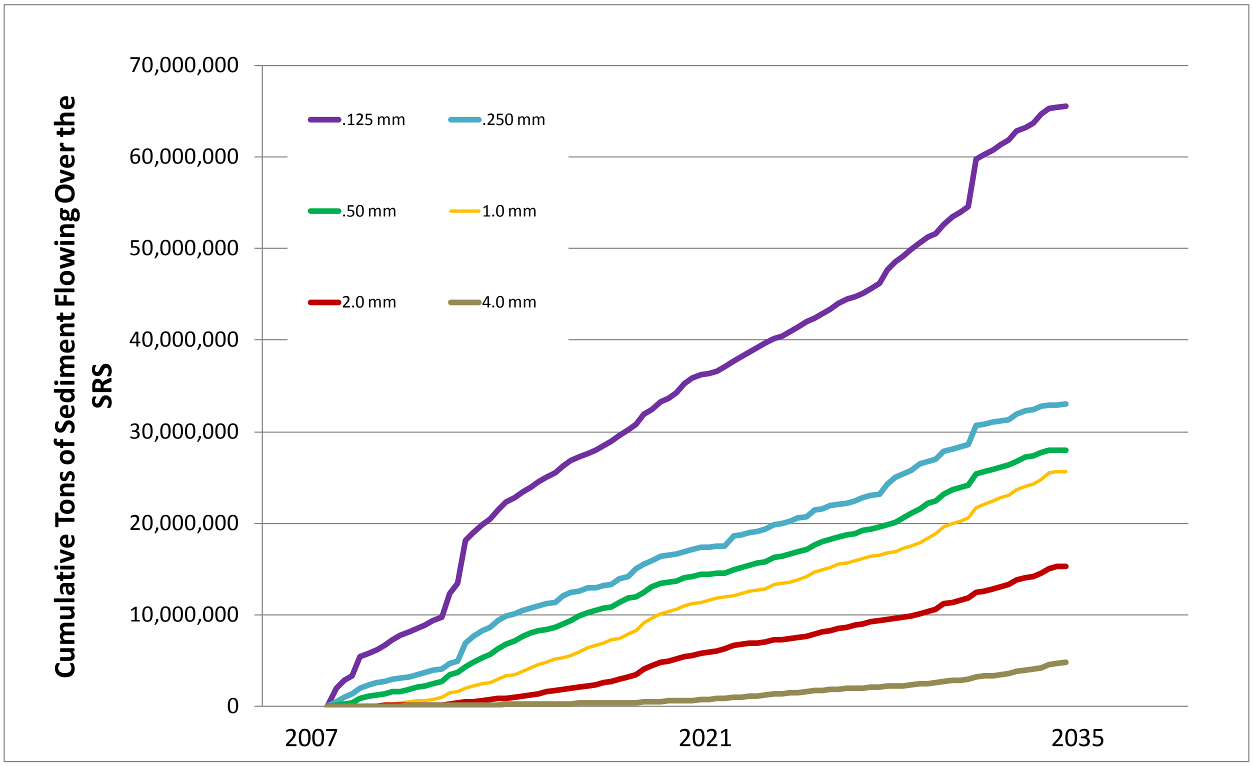

Figure 3.52 28-year FEDS Run – Cumulative Tons of Sediment Flowing over the SRS

3.3.5 Summary

This study utilized a new 2-D model to predict the evolution of the North Fork of the Toutle River sediment plain above the SRS over the FEDS. After this FEDS study, this model will be used to evaluate sediment management strategies in the North Fork of the Toutle River above the SRS.

About 14 M Tons of sediment enter the study reach at N1 in the modeled 3-year calibration period. The 2-D model results indicate that the SRS, which by 1998 passes flow over the spillway crest, is approximately 30% efficient at trapping sediment at present. The calibration results, which agree volumetrically with the observed difference between the 2003 and 2006 LiDAR surveyed surfaces, show over 10 M Tons of sediment passing over the SRS between WYs 2004 and 2006.

The 28-year model projection of future performance of the SRS over the FEDS period through 2035 shows the SRS cumulative sediment trapping efficiency decreasing to 20% over that period. The sediment plain will continue to trap some sediment until it reaches an equilibrium slope at some point in the post-FEDS future. The model indicates that about 80% of the 215 M Tons of sediment projected to enter the system at N1 over the FEDS period can be expected to enter the Toutle River below the SRS.

FEDS 2-D modeling results which simulate the performance of the existing SRS structure through 2035, show that the sediment plain is expected to increase in scale. Consequently, as

time passes the SRS will not trap as much sediment as it does today. With decreased trapping efficiency in the SRS, more sediment will reach the Toutle River below the SRS, and ultimately the Cowlitz and the Columbia Rivers.

Sediment management strategies can be evaluated with the 2-D model of the North Fork of the Toutle River. Additionally, predicted sediment output from this model and the accompanying 1-D hydraulic model above the SRS are used as input on a 1-D model of the Lower Cowlitz River. The Lower Cowlitz 1-D model provides input for a 2-D model of the Lower Cowlitz River, which extends from just upstream of the Columbia River confluence to about Cowlitz River Mile (RM) 4.5. The suite of Toutle and Cowlitz CFD models will provide support for sediment management in the Cowlitz River Basin moving forward.

3.4 Summary of 1-D/2-D Models and Sediment Budget Long-term Forecasting

Long-term forecasting results of the 1-D and 2-D sediment transport models as well as projections using the Sediment Budget were compared. Table 3.4 provides a summary of sediment inflow, deposition, outflow, and trap efficiency for all three models. Modeling results by grain class are also provided in Table 3.5, Table 3.6, and Table 3.7.

Table 3.4 Summary of Sediment Input, Output, Deposition, and Trap Efficiency above the SRS from the Sediment Budget, 1-D HEC-RAS Modeling, and 2-D MIKE 21C Modeling

2007 to 2035 Forecasting Period Model Results – Existing Conditions													
		Annual Debris Avalanche Erosion			Annual SRS Deposition			Annual Output from SRS			Annual Trap Efficiency		
Surrogate Year	Forecast Year	Sediment Budget (tons)	1-D Model (tons)	2-D Model (tons)	Sediment Budget (tons)	1-D Model (tons)	2-D Model (tons)	Sediment Budget (tons)	1-D Model (tons)	2-D Model (tons)	Sediment Budget (%)	1-D Model (%)	2-D Model (%)
2003	2008	8,092,556	7,476,633	9,184,771	3,454,201	1,722,504	3,861,745	4,638,355	5,754,129	5,323,026	43	23	42
2006	2009	6,732,368	6,398,457	8,015,365	2,057,315	1,436,865	2,140,573	4,675,052	4,961,592	5,874,792	31	22	27
2005	2010	4,420,128	3,593,320	1,826,019	2,057,315	550,976	667,719	2,362,813	3,042,344	1,158,300	47	15	37
2004	2011	2,993,925	2,546,910	1,499,560	898,168	105,096	747,854	2,095,756	2,441,814	751,706	30	04	50
2006	2012	6,732,368	6,394,960	7,784,958	2,057,315	1,698,599	4,035,481	4,675,052	4,696,361	3,749,477	31	27	52
2004	2013	2,993,925	2,545,140	1,517,704	898,168	141,209	453,881	2,095,756	2,403,931	1,063,823	30	06	30
2003	2014	8,092,556	7,481,260	7,665,750	3,454,201	1,933,967	1,400,059	4,638,355	5,547,293	6,265,691	43	26	00
2007	2015	26,197,656	25,017,920	26,877,329	8,788,236	12,808,836	7,543,248	17,409,420	12,209,084	19,334,080	34	51	28
2002	2016	10,523,145	10,124,170	9,837,736	4,578,825	1,977,587	2,037,055	5,944,320	8,146,583	7,800,680	44	20	21
2003	2017	8,092,556	7,488,240	8,991,506	3,454,201	1,494,830	3,751,692	4,638,355	5,993,410	5,239,814	43	20	42
2001	2018	384,289	227,470	0	-162,102	-229,565	0	546,391	457,035	0	-42	-101	
2006	2019	6,732,368	6,391,820	7,784,958	2,057,315	1,369,060	2,038,077	4,675,052	5,022,760	5,746,881	31	21	26
2003	2020	8,092,556	7,482,280	9,148,933	3,454,201	1,500,069	3,809,274	4,638,355	5,982,211	5,339,659	43	20	42
1999	2021	11,377,532	11,064,920	14,776,495	8,534,135	2,295,478	-730,181	2,843,397	8,769,442	15,506,676	75	21	-5
2004	2022	2,993,925	2,545,900	2,011,385	898,168	113,454	600,196	2,095,756	2,432,446	1,411,189	30	04	30
2005	2023	4,420,128	3,592,300	1,320,889	2,057,315	405,950	159,685	2,362,813	3,186,350	1,161,204	47	11	12
2000	2024	946,244	900,800	1,278,273	-2,838,613	-749,589	-1,236,355	3,784,857	1,650,389	2,514,628	-300	-83	-97
2006	2025	6,732,368	6,391,200	7,931,873	2,057,315	1,321,925	1,401,753	4,675,052	5,069,275	6,530,120	31	21	18
2002	2026	10,523,145	10,110,400	9,877,183	4,578,825	1,815,578	2,790,042	5,944,320	8,294,822	7,087,142	44	18	28
2006	2027	6,732,368	6,401,900	9,079,198	2,057,315	1,092,558	340,781	4,675,052	5,309,342	8,738,417	31	17	04
2002	2028	10,523,145	10,110,400	9,837,736	4,578,825	1,775,547	3,328,956	5,944,320	8,334,853	6,508,780	44	18	34
2001	2029	384,289	230,900	0	-162,102	-116,636	0	546,391	347,536	0	-42	-51	
2007	2030	26,197,656	25,011,300	25,117,402	8,788,236	11,069,429	13,040,620	17,409,420	13,941,871	12,076,782	34	44	52
2002	2031	10,523,145	10,124,200	11,458,653	4,578,825	1,552,711	-1,945,498	5,944,320	8,571,489	13,404,151	44	15	-17
2003	2032	8,092,556	7,488,200	7,639,595	3,454,201	1,364,488	-4,488,136	4,638,355	6,123,712	12,127,731	43	18	-59
2005	2033	4,420,128	3,595,800	3,302,161	2,057,315	313,891	147,686	2,362,813	3,281,909	3,154,475	47	9	4
2002	2034	10,523,145	10,112,100	9,767,297	4,578,825	1,730,902	-951,890	5,944,320	8,381,198	10,719,187	44	17	-10
2000	2035	946,244	905,000	1,583,153	-2,838,613	-556,381	-2,153,012	3,784,857	1,461,381	3,736,165	-300	-61	-136
	Total	**215,416,414**	**201,753,900**	**215,115,882**	**79,427,337**	**49,939,339**	**42,791,306**	**135,989,077**	**151,814,561**	**172,324,576**	**37**	**25**	**20**

Table 3.5 Sediment Budget Annual Sediment Output from the SRS by Grain Size

Sediment Budget – Annual Sediment Output from the SRS (tons) [A]												
Forecast Year	**Surrogate Year**	**Total**	**Silt/Clay 0.0625**	**VFS 0.125**	**FS 0.25**	**MS 0.5**	**CS 1**	**VCS 2**	**VFG 4**	**FG 8**	**MG 16**
2008	2003	4,638,355	2,278,645	1,197,339	803,261	129,449	136,106	93,554	0	0	0
2009	2006	4,675,052	2,035,235	1,127,736	868,594	314,826	204,461	124,199	0	0	0
2010	2005	2,362,813	1,202,981	630,947	421,334	42,062	38,021	27,468	0	0	0
2011	2004	2,095,756	1,002,730	539,865	318,296	31,351	111,321	92,194	0	0	0
2012	2006	4,675,052	2,035,235	1,127,736	868,594	314,826	204,461	124,199	0	0	0
2013	2004	2,095,756	1,002,730	539,865	318,296	31,351	111,321	92,194	0	0	0
2014	2003	4,638,355	2,278,645	1,197,339	803,261	129,449	136,106	93,554	0	0	0
2015	2007	17,409,420	7,855,420	4,172,719	2,211,246	1,451,186	1,078,315	640,534	0	0	0
2016	2002	5,944,320	2,946,762	1,543,158	1,025,085	147,572	166,042	115,702	0	0	0
2017	2003	4,638,355	2,278,645	1,197,339	803,261	129,449	136,106	93,554	0	0	0
2018	2001	546,391	148,705	95,517	103,753	100,428	63,483	34,504	0	0	0
2019	2006	4,675,052	2,035,235	1,127,736	868,594	314,826	204,461	124,199	0	0	0
2020	2003	4,638,355	2,278,645	1,197,339	803,261	129,449	136,106	93,554	0	0	0
2021	1999	2,843,397	1,748,958	778,290	316,149	0	0	0	0	0	0
2022	2004	2,095,756	1,002,730	539,865	318,296	31,351	111,321	92,194	0	0	0
2023	2005	2,362,813	1,202,981	630,947	421,334	42,062	38,021	27,468	0	0	0
2024	2000	3,784,857	977,706	920,225	840,350	503,124	296,998	246,454	0	0	0
2025	2006	4,675,052	2,035,235	1,127,736	868,594	314,826	204,461	124,199	0	0	0
2026	2002	5,944,320	2,946,762	1,543,158	1,025,085	147,572	166,042	115,702	0	0	0
2027	2006	4,675,052	2,035,235	1,127,736	868,594	314,826	204,461	124,199	0	0	0
2028	2002	5,944,320	2,946,762	1,543,158	1,025,085	147,572	166,042	115,702	0	0	0
2029	2001	546,391	148,705	95,517	103,753	100,428	63,483	34,504	0	0	0
2030	2007	17,409,420	7,855,420	4,172,719	2,211,246	1,451,186	1,078,315	640,534	0	0	0
2031	2002	5,944,320	2,946,762	1,543,158	1,025,085	147,572	166,042	115,702	0	0	0
2032	2003	4,638,355	2,278,645	1,197,339	803,261	129,449	136,106	93,554	0	0	0
2033	2005	2,362,813	1,202,981	630,947	421,334	42,062	38,021	27,468	0	0	0
2034	2002	5,944,320	2,946,762	1,543,158	1,025,085	147,572	166,042	115,702	0	0	0
2035	2000	3,784,857	977,706	920,225	840,350	503,124	296,998	246,454	0	0	0
Total		**135,989,077**	**62,632,964**	**34,008,813**	**22,330,436**	**7,288,957**	**5,858,660**	**3,869,247**	**0**	**0**	**0**

[A] VFS = very fine sand, FS = fine sand, MS = medium sand, CS = coarse sand, VCS = very coarse sand, VFG = very fine gravel, FG = fine gravel, MG = medium gravel

Table 3.6 1-D Model Annual Sediment Output from the SRS by Grain Size

1-D Model Results – Annual Output from the SRS (tons)											
Forecast Year	**Surrogate Year**	**Total**	**Silt/Clay 0.0625**	**VFS 0.125**	**FS 0.25**	**MS 0.5**	**CS 1**	**VCS 2**	**VFG 4**	**FG 8**	**MG 16**
2008	2003	5,754,129	2,022,138	1,400,120	1,327,365	755,603	220,517	27,806	528	53	0
2009	2006	4,961,592	1,746,563	796,022	985,126	795,366	467,324	168,503	2,612	73	3
2010	2005	3,042,344	1,295,215	561,633	548,005	343,437	187,125	87,392	19,527	10	0
2011	2004	2,441,814	997,557	428,564	437,664	277,238	179,475	92,982	28,321	14	0
2012	2006	4,696,361	1,745,688	792,569	915,761	644,634	386,603	152,774	58,244	89	0
2013	2004	2,403,931	997,057	429,442	440,735	264,939	145,543	88,400	37,799	17	0
2014	2003	5,547,293	1,988,917	1,330,873	1,160,565	662,317	288,856	78,780	36,910	74	1
2015	2007	12,209,084	4,521,465	3,450,660	2,335,319	1,278,347	461,785	136,212	25,205	88	3
2016	2002	8,146,583	2,980,234	1,356,337	1,546,604	1,253,764	734,840	253,741	21,051	11	0
2017	2003	5,993,410	1,991,701	1,331,040	1,194,526	774,271	437,761	204,376	59,692	42	1
2018	2001	457,035	129,325	47,130	61,110	64,004	69,498	75,502	10,466	0	0
2019	2006	5,022,760	1,743,831	794,050	981,660	797,211	424,687	183,290	97,867	163	1
2020	2003	5,982,211	1,989,757	1,335,530	1,169,580	759,514	444,682	200,111	81,633	1,403	1
2021	1999	8,769,442	2,879,456	1,466,610	1,617,540	1,356,155	832,379	414,600	184,330	18,372	1
2022	2004	2,432,446	997,282	429,720	443,080	277,560	167,410	77,300	37,651	2,442	0
2023	2005	3,186,350	1,293,968	561,440	551,280	387,200	242,751	111,180	34,928	3,602	0
2024	2000	1,650,389	443,661	183,030	256,830	274,290	226,820	157,864	90,066	17,828	0
2025	2006	5,069,275	1,743,605	798,980	1,004,210	804,210	431,124	188,566	64,169	34,409	1
2026	2002	8,294,822	2,973,335	1,331,230	1,457,620	1,226,700	785,542	361,193	128,228	30,974	1
2027	2006	5,309,342	1,747,979	795,930	996,160	851,740	517,865	269,754	108,005	21,908	1
2028	2002	8,334,853	2,973,395	1,330,480	1,459,270	1,249,520	793,344	359,601	146,039	23,204	0
2029	2001	347,536	130,302	44,220	46,490	36,630	33,625	29,963	25,899	407	0
2030	2007	13,941,871	4,520,598	3,580,170	2,831,480	1,863,170	780,837	255,420	78,836	31,357	3
2031	2002	8,571,489	2,979,530	1,342,170	1,509,450	1,303,950	875,448	411,614	132,717	16,610	0
2032	2003	6,123,712	1,992,446	1,346,770	1,234,570	826,350	455,000	193,890	65,959	8,727	0
2033	2005	3,281,909	1,295,557	562,360	560,210	401,770	265,910	136,961	55,094	4,047	0
2034	2002	8,381,198	2,974,339	1,335,950	1,476,300	1,247,650	807,330	378,958	134,857	25,813	1
2035	2000	1,461,381	443,790	176,540	223,330	216,040	169,710	124,825	94,066	13,079	0
Total		**151,814,561**	**53,538,690**	**29,339,570**	**28,771,840**	**20,993,580**	**11,833,790**	**5,221,558**	**1,860,700**	**254,815**	**18**

Table 3.7 2-D Model Annual Sediment Output from the SRS by Grain Size

2-D Model Results – Annual Output from the SRS (tons)											
Forecast Year	**Surrogate Year**	**Total**	**Silt/Clay 0.0625**	**VFS 0.125**	**FS 0.25**	**MS 0.5**	**CS 1**	**VCS 2**	**VFG 4**	**FG 8**	**MG 16**
2008	2003	5,323,025	2,205,468	1,187,559	1,424,025	389,750	65,823	33,083	17,317	0	0
2009	2006	5,874,792	2,103,490	1,132,649	1,326,857	1,039,294	183,622	54,293	34,587	0	0
2010	2005	1,158,300	464,510	250,121	222,996	140,285	57,919	9,531	12,939	0	0
2011	2004	751,706	262,246	141,209	129,437	112,426	82,022	15,370	8,996	0	0
2012	2006	3,749,478	1,043,494	561,881	837,278	802,886	417,136	58,409	28,394	0	0
2013	2004	1,063,822	262,893	141,558	202,136	248,033	189,630	13,807	5,765	0	0
2014	2003	6,265,692	2,359,884	1,270,707	841,033	936,633	655,633	166,320	35,482	0	0
2015	2007	19,334,080	5,831,975	3,140,294	4,911,053	3,163,745	1,641,355	574,780	70,878	0	0
2016	2002	7,800,681	1,708,774	920,109	1,275,296	1,612,753	1,582,316	652,242	49,191	0	0
2017	2003	5,239,813	1,181,952	636,436	1,260,671	965,322	744,302	401,795	49,335	0	0
2018	2001	0	0	0	0	0	0	0	0	0	0
2019	2006	5,746,882	1,099,421	591,996	782,193	1,271,283	1,313,071	612,313	76,605	0	0
2020	2003	5,339,659	1,064,375	573,125	1,004,094	1,133,543	930,768	591,844	41,910	0	0
2021	1999	15,506,676	3,310,854	1,782,767	2,671,102	2,197,453	3,075,986	2,260,429	208,085	0	0
2022	2004	1,411,189	379,027	204,091	201,970	187,517	228,182	169,144	41,258	0	0
2023	2005	1,161,204	280,209	150,882	244,414	169,116	139,645	137,893	39,046	0	0
2024	2000	2,514,628	536,457	288,861	182,970	194,741	653,263	514,885	143,451	0	0
2025	2006	6,530,120	1,371,539	738,521	1,628,569	1,057,969	766,245	670,781	296,496	0	0
2026	2002	7,087,143	1,476,405	794,987	1,396,591	1,301,117	1,137,504	604,681	375,858	0	0
2027	2006	8,738,418	1,671,293	899,927	1,549,686	1,615,136	1,647,485	983,148	371,743	0	0
2028	2002	6,508,781	1,407,211	757,729	1,119,812	1,048,702	1,067,860	845,240	262,227	0	0
2029	2001	0	0	0	0	0	0	0	0	0	0
2030	2007	12,076,781	2,909,845	1,566,840	3,261,859	1,987,240	1,327,796	770,749	252,452	0	0
2031	2002	13,404,151	2,512,594	1,352,935	2,057,418	2,573,614	2,699,817	1,642,602	565,171	0	0
2032	2003	12,127,731	3,722,484	2,004,415	2,289,416	1,530,111	1,444,473	838,770	298,062	0	0
2033	2005	3,154,475	678,729	365,469	344,359	456,295	703,339	421,574	184,710	0	0
2034	2002	10,719,188	2,174,720	1,171,003	1,597,715	1,572,131	1,969,099	1,467,325	767,195	0	0
2035	2000	3,736,165	555,565	299,151	211,855	288,816	903,210	839,839	637,729	0	0
Total		**172,324,580**	**42,575,412**	**22,925,222**	**32,974,805**	**27,995,911**	**25,627,501**	15,350,847	**4,874,882**	**0**	**0**

3.4.1 Sediment Input at N1

Annual and cumulative sediment input at N1 through 2035 are shown graphically in Figure 3.53 and Figure 3.54, respectively. The Sediment Budget was used to develop inflowing sediment loads at N1; however, the annual input is slightly different when comparing 1-D and 2-D values to sediment budget numbers. Sediment input to the 1-D model is approximately 6% less than the Sediment Budget by 2035 due to the exclusion of 600 cfs and less from the inflow hydrograph. The annual inflowing sediment to the 2-D model varies from the Sediment Budget to redistribute sediment inflow to accommodate the compression of the hydrograph resulting in reasonable computation times. Although the annual sediment load differs in the 2-D model, the cumulative value by 2035 matches the Sediment Budget. Differences in sediment input to the 1-D and 2-D models are considered to be within the uncertainty identified in the Sediment Budget.

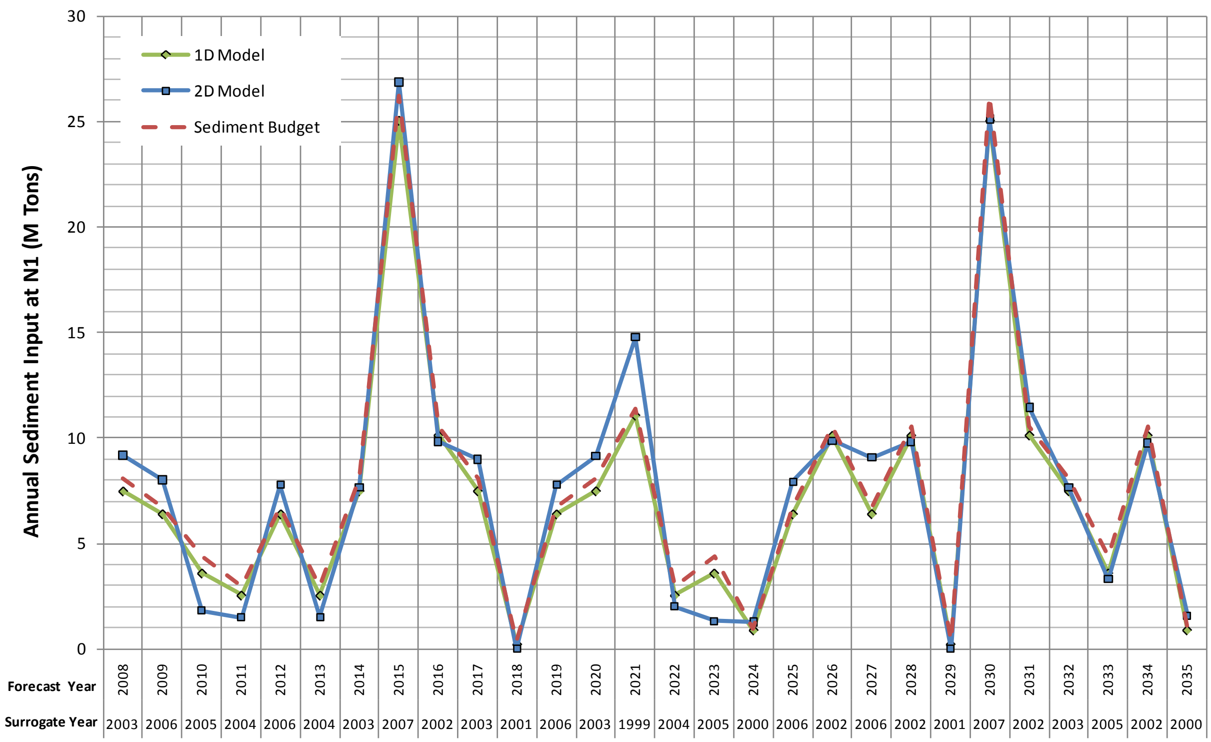

Figure 3.53 Annual Sediment Input at N1

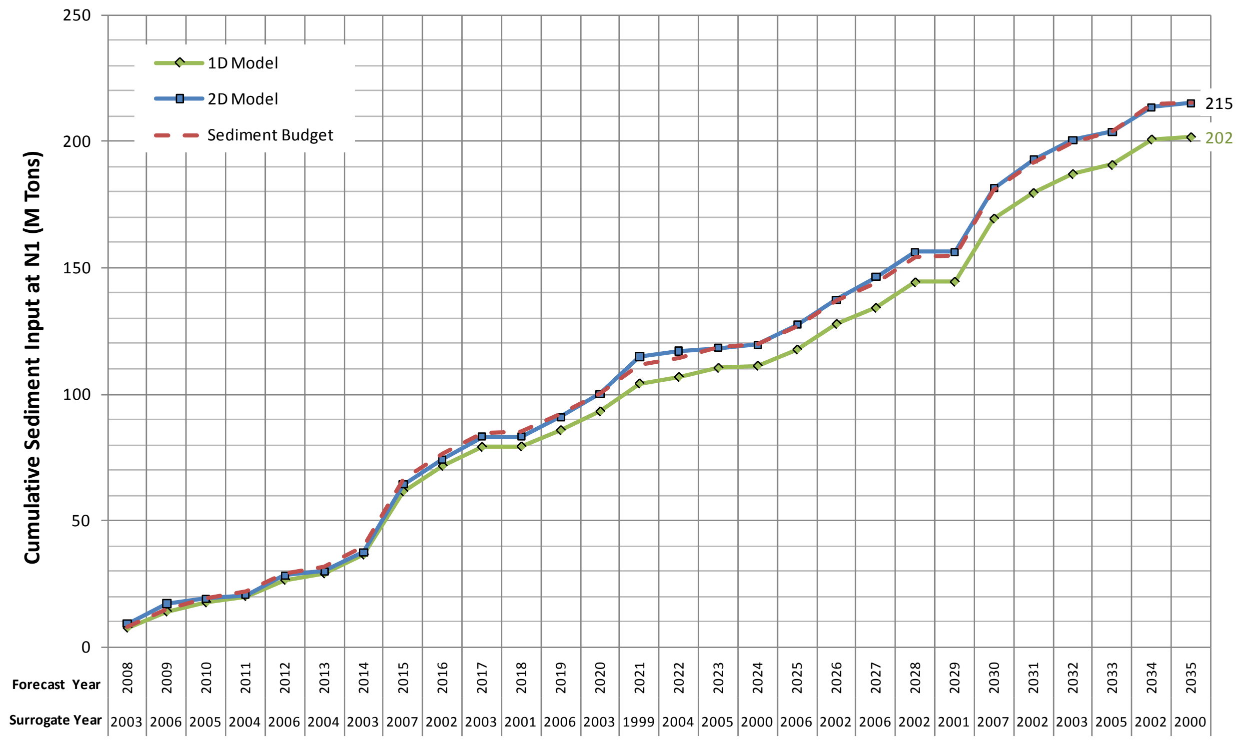

Figure 3.54 Cumulative Sediment Input at N1 through 2035

Note that the highest annual inflowing sediment loads occur in 2015 and 2030, both corresponding to the 2007 surrogate year in which the Nov 2006 event is replicated. The lowest annual sediment load occurs in 2018 and 2029 representing the surrogate year of 2001.

3.4.2 Sediment Deposition Above the SRS

Plots of annual and cumulative sediment deposition above the SRS through the forecast period are provided in Figure 3.55 and Figure 3.56, respectively. Three distinct periods of sediment plain evolution can be seen in each of the modeling approaches over the 28-year forecast period. From 2008 to 2014, sediment inflow is relatively low and the sediment plain is slowly growing. In 2015 (surrogate year 2007) the largest sediment inflow year event occurs and a significant amount about 10 M Tons of sediment are shown to deposit in each model. The period following this event until 2030 (which is again surrogate year 2007) shows a slowly growing sediment plain in both the 1-D and 2-D models (the sediment budget model predicts more sediment plain growth during this period due to replication of previous years without decreased trapping efficiency). Following 2030, the 1-D model predicts very slow or stalled growth of the sediment plain and the 2-D model actually shows the forming of primary channels that efficiently transport material out of the sediment plain. The sediment budget model builds to peak sediment storage in 2034, and all three models predict a slight decrease in storage in 2035, attributed to the small amount of inflowing sediment and scour occurring on the sediment plain. While the sediment budget model is showing a continuing increase in volume of the sediment plain through 2035, the 1-D and 2-D models are showing a trend after 2030 that

indicates a period where the sediment plain has filled to a point where little additional sediment is being stored upstream of the SRS. In summary, the 1-D and 2-D models indicate increased transport of sediment to the Toutle River, while the Sediment Budget continues to indicate increasing deposition.

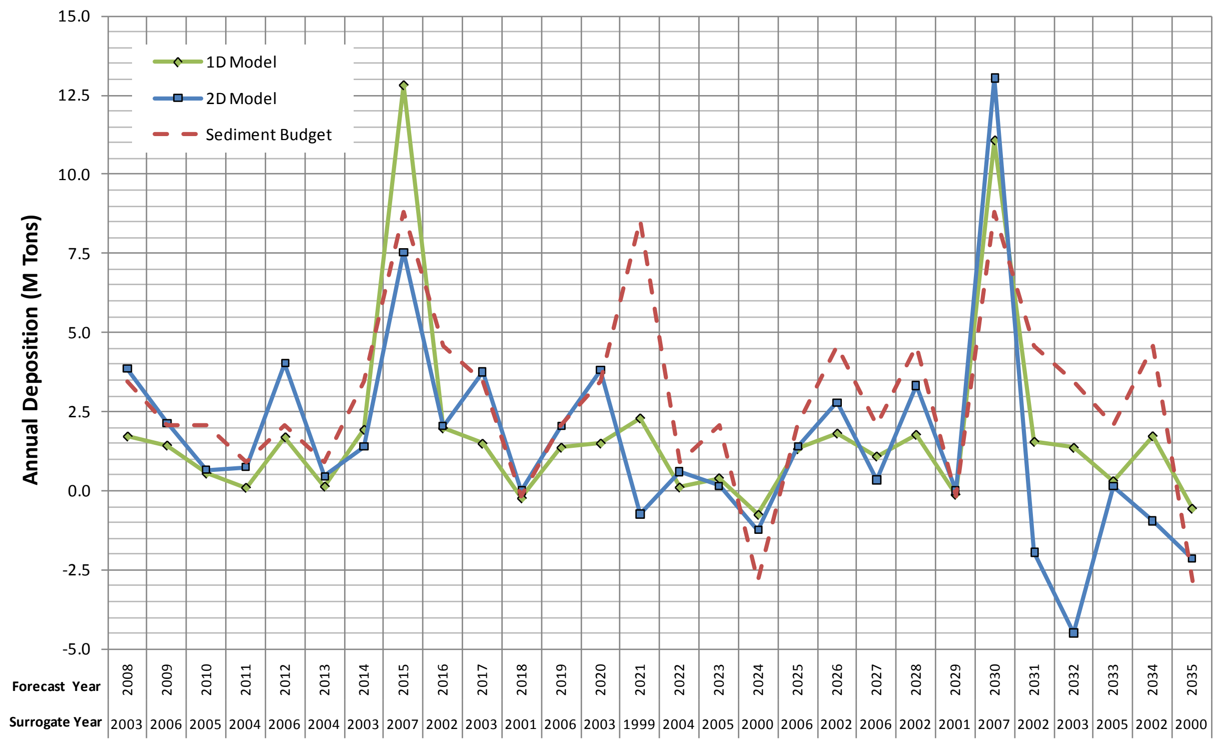

Figure 3.55 Annual Sediment Deposition above the SRS

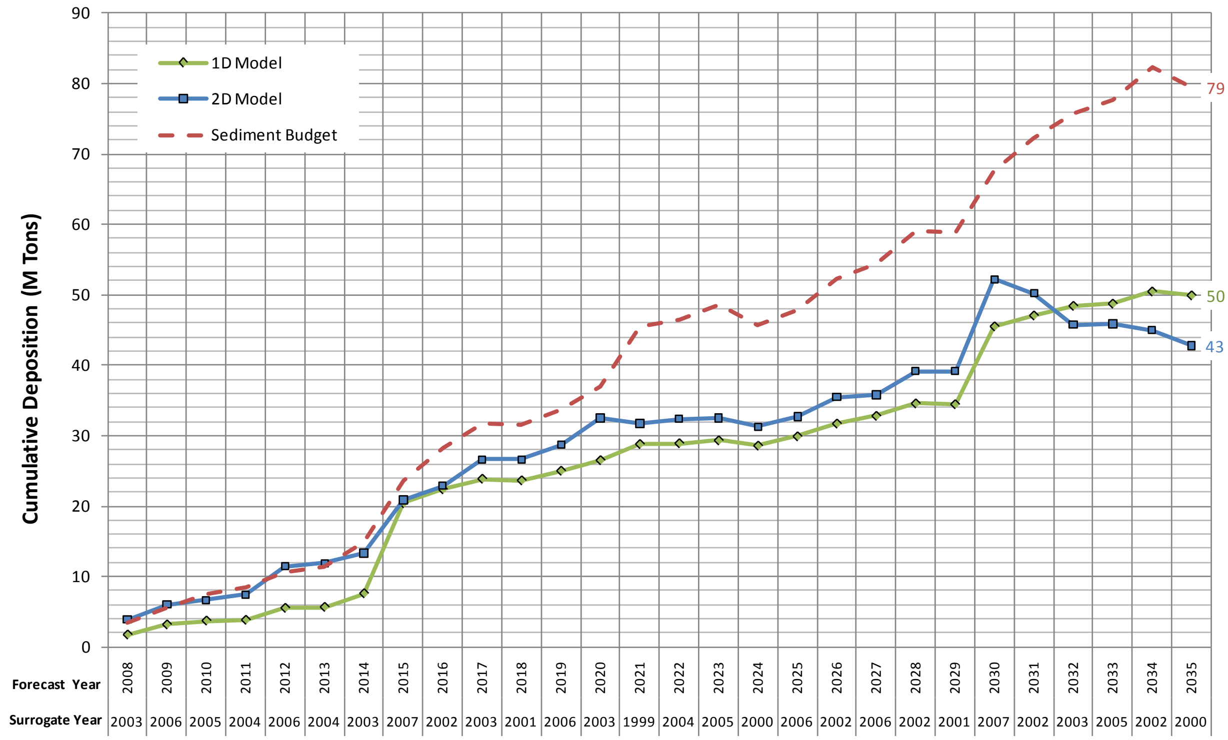

Figure 3.56 Cumulative Deposition above the SRS through 2035

3.4.3 SRS Trap Efficiency

Long-term forecast trap efficiency of the sediment plain above the SRS computed on an annual basis is shown graphically in Figure 3.57. Trap efficiency is highly variable from year to year and likely dependent upon the hydrology, inflowing sediment load, and current geometry of the sediment plain. Field observations and survey data indicate that channels frequently are formed, migrate about the sediment plain, and are filled in. Moderately- to well-formed channels tend to focus flow providing an efficient conduit for moving sediment, whereas the wide sediment plain spreads flow across the valley resulting in sediment deposition. Note that in all three models the annual trap efficiency was negative for some years, indicating that there was more sediment flowing over the SRS spillway than was coming into the system. If low sediment load conditions are present the hydraulics are more than sufficient to scour sands and silts from the sediment plain.

Figure 3.57 Annual Trap Efficiency

Long-term trap efficiency above the SRS was also evaluated using cumulative sediment inflow and outflow. Cumulative trap efficiency through the forecast period, shown in Figure 3.58, computed by the 1-D and 2-D models shows a declining trend. Note that the sediment budget results do not take declining trap efficiency into account. In comparison, the overall long-term ability of the SRS to trap sediment is predicted by the 1-D and 2-D models to be 25% and 20%, respectively. The cumulative trap efficiency computed by the Sediment Budget between 1999 and 2007 was 37%.

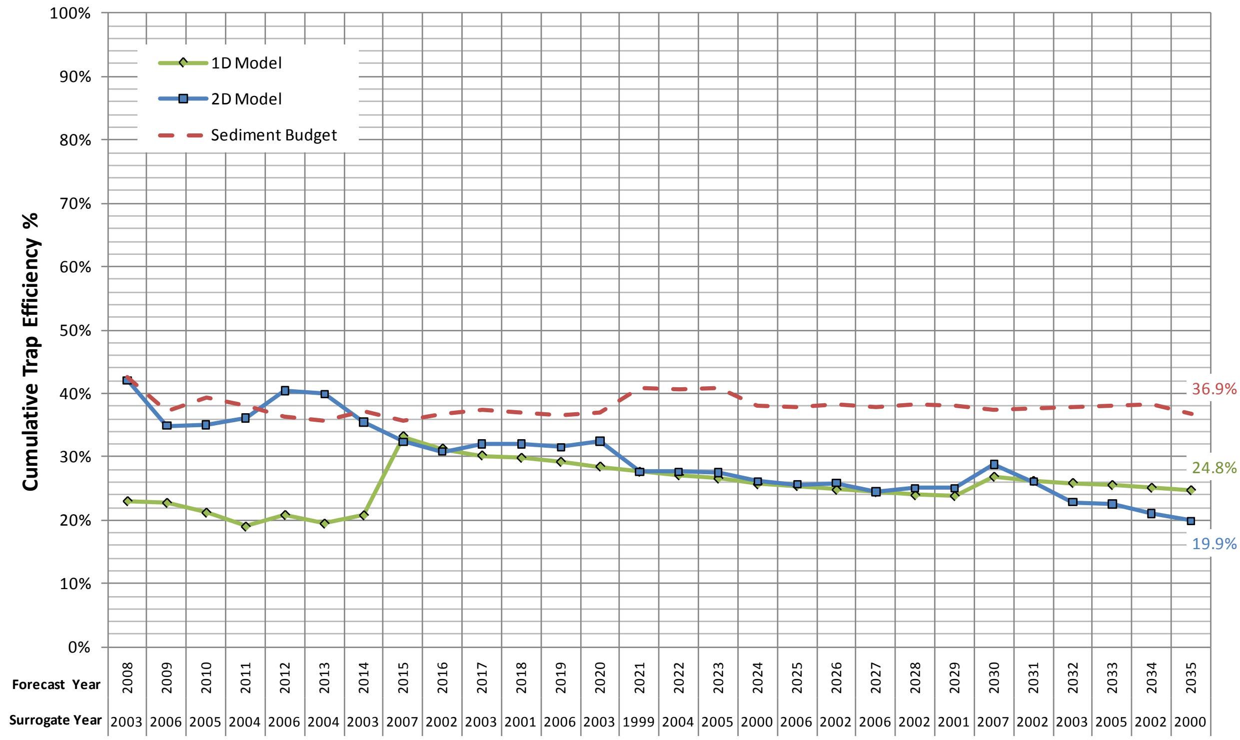

Figure 3.58 Cumulative Trap Efficiency of the SRS through 2035

3.4.4 Sediment Output from the SRS

Graphical plots of annual and cumulative sediment output from the SRS over the forecast period are provided in Figure 3.59 and Figure 3.60, respectively. Comparison of the Sediment Budget to the 1-D and 2-D output shows a deviation occurring around 2018, which is consistent with the overall decline in trap efficiency. The total sediment output by 2035 computed by the 1-D and 2-D models are 152 and 172 M Tons, respectively, a difference of approximately 12%. The total sediment output in 2035 by grain size is shown graphically in Figure 3.61.

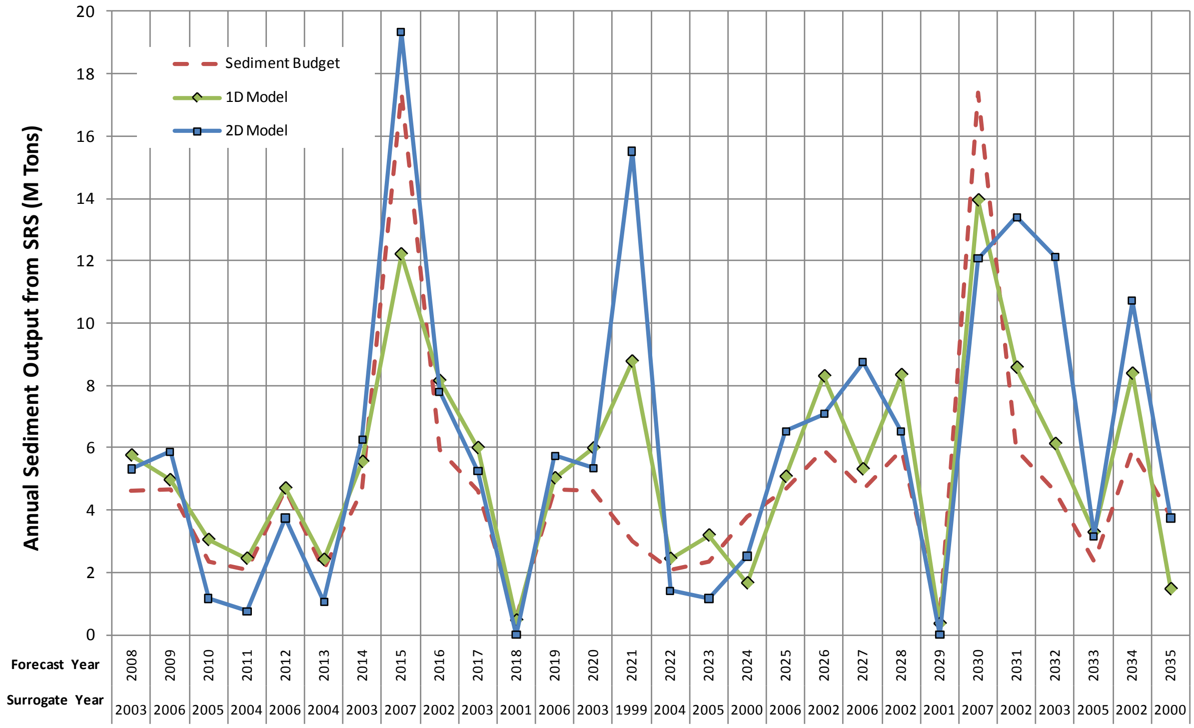

Figure 3.59 Annual Sediment Output from the SRS

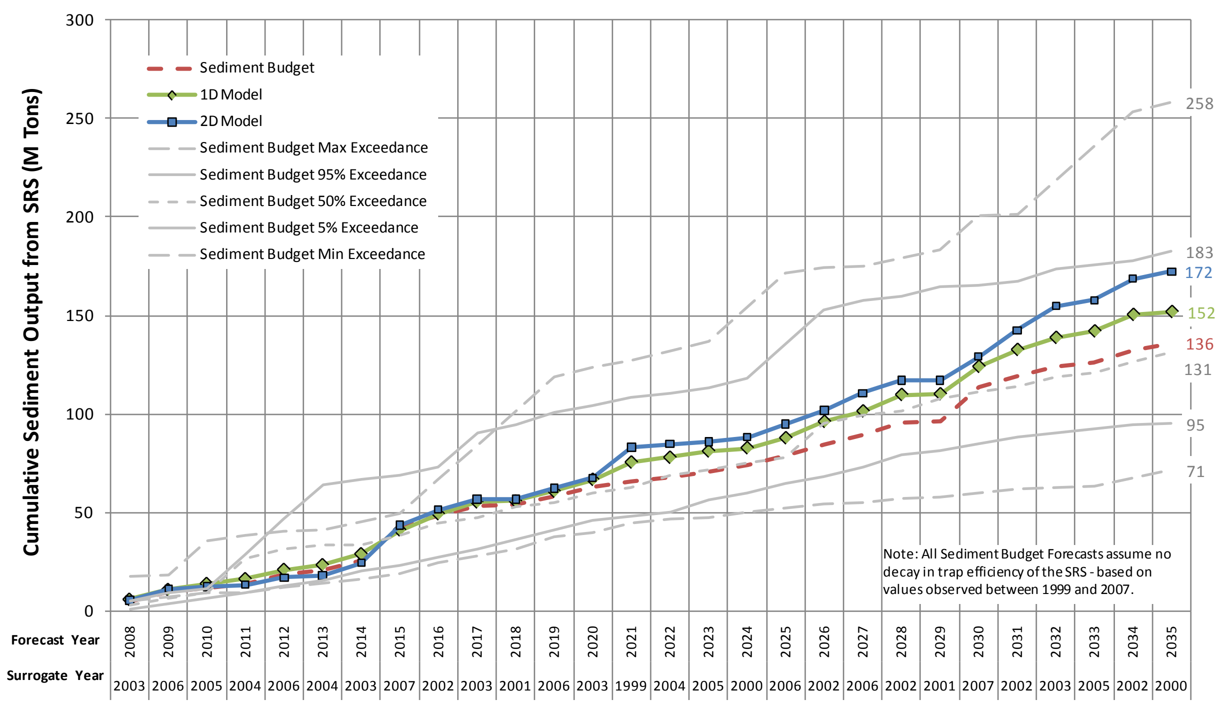

Figure 3.60 Cumulative Sediment Output from the SRS through 2035

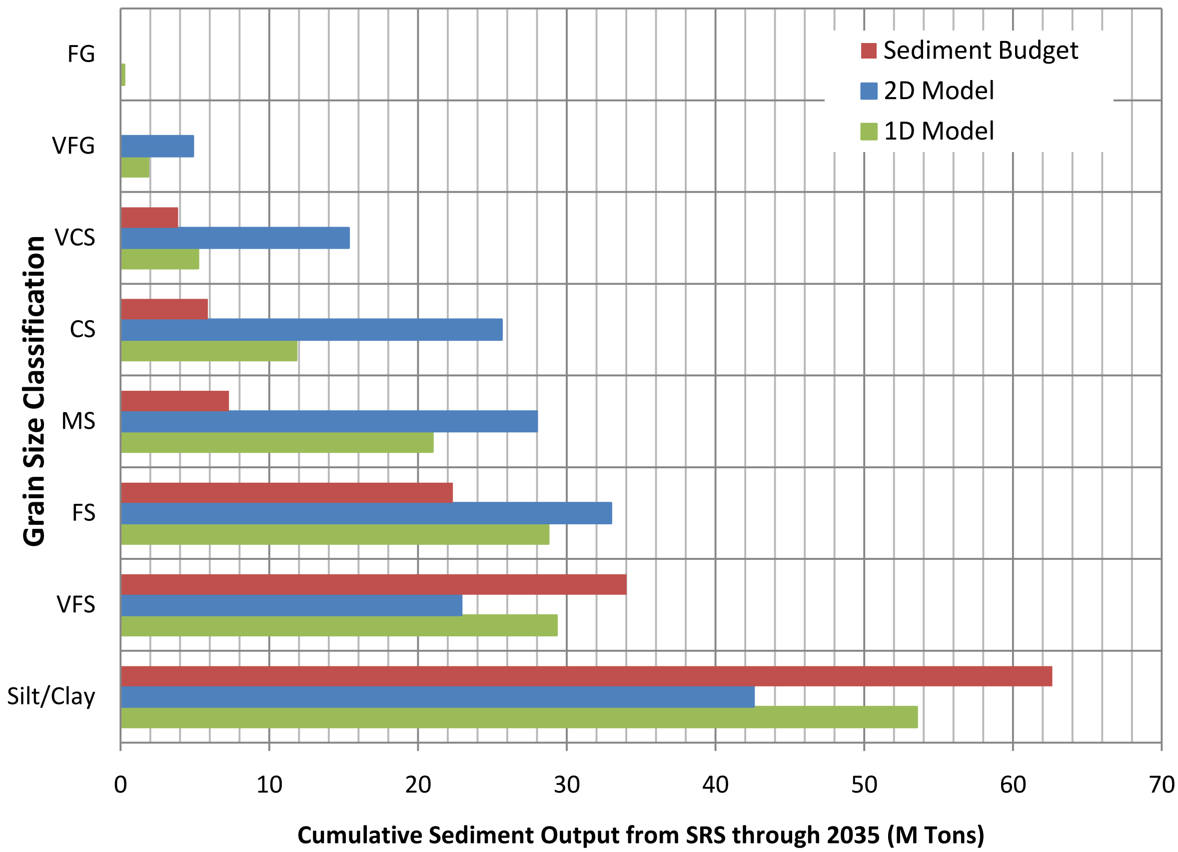

Figure 3.61 Cumulative Sediment Output by Grain Size from the SRS through 2035

4.0 NORTH FORK, SOUTH FORK, TOUTLE RIVERS BELOW THE SRS

The Toutle River system below the SRS is a transport reach for sand-sized material that passes through the SRS spillway. Additional sources of sediment are introduced in this reach including the inflow from the Green and South Fork Rivers, and bank erosion throughout the system. A spreadsheet analysis using outputs from upstream models along with the Sediment Budget and USGS suspended sediment gage data is used in this area to develop sediment loads for use in Cowlitz River models.

4.1 Toutle Basin Sediment Sources below the SRS

A breakdown of all Toutle Basin sediment sources estimated in the 2010 SBR from 1999 to 2007 are shown graphically in Figure 4.1. The annual values of sediment sources by grain size below the SRS for WYs 1999 through 2007, used as surrogate years in long-term forecasting, is shown in Table 4.1. Toutle Basin sediment sources are made up of approximately 8% gravel, 69% sand, and 23% silts and clays. Breakdown of the annual basin sediment sources by grain size is presented in tabular form in Table 4.2 and shown graphically in Figure 4.2.

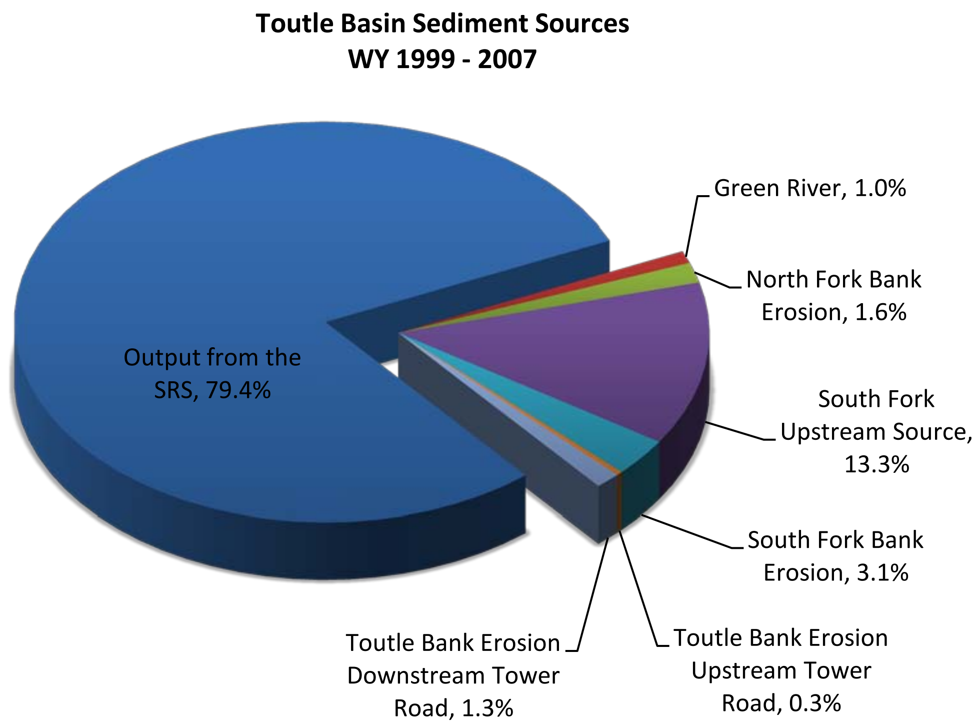

Figure 4.1 Toutle Basin Sediment Source Breakdown for WYs 1999 through 2007 (from the 2010 SBR)

Table 4.1 Toutle Basin Sediment Sources by Grain Size below the SRS (Sediment Budget)

		Annual Sediment Sources between the SRS and Mouth of Toutle River (Tons)										
Surrogate Year	**Total**	**Silt/Clay 0.0625**	**VFS 0.125**	**FS 0.25**	**MS 0.5**	**CS 1**	**VCS 2**	**VFG 4**	**FG 8**	**MG 16**	**CG 32**	**VCG 64**
1999	2,035,838	486,080	315,052	519,861	421,691	124,203	38,199	38,583	26,252	28,909	24,215	12,793
2000	766,429	151,181	97,578	163,651	153,532	61,131	26,947	33,170	22,569	24,853	20,818	10,998
2001	89,142	13,604	8,293	14,233	16,964	9,192	4,939	6,468	4,400	4,846	4,059	2,144
2002	1,498,276	351,010	227,415	375,809	309,238	94,447	30,770	32,338	22,002	24,230	20,296	10,722
2003	627,855	89,982	61,129	106,586	122,231	62,988	33,494	44,690	30,407	33,485	28,048	14,818
2004	460,958	83,309	54,911	93,089	91,799	39,367	18,527	23,594	16,053	17,678	14,808	7,823
2005	466,271	97,798	62,958	104,956	94,216	34,729	14,232	16,932	11,521	12,687	10,627	5,614
2006	611,511	113,391	72,910	122,979	121,219	52,152	24,446	30,811	20,964	23,086	19,337	10,216
2007	5,326,686	1,357,690	879,537	1,443,854	1,116,559	287,210	66,873	51,629	35,128	38,684	32,403	17,119

Table 4.2 Annual Percentage by Grain Class of Sediment Sources below the SRS

	% of Annual Sediment Sources between the SRS and Mouth of Toutle River										
Surrogate Year	**Silt/Clay 0.0625**	**VFS 0.125**	**FS 0.25**	**MS 0.5**	**CS 1**	**VCS 2**	**VFG 4**	**FG 8**	**MG 16**	**CG 32**	**VCG 64**
1999	23.9%	15.5%	25.5%	20.7%	6.1%	1.9%	1.9%	1.3%	1.4%	1.2%	0.6%
2000	19.7%	12.7%	21.4%	20.0%	8.0%	3.5%	4.3%	2.9%	3.2%	2.7%	1.4%
2001	15.3%	9.3%	16.0%	19.0%	10.3%	5.5%	7.3%	4.9%	5.4%	4.6%	2.4%
2002	23.4%	15.2%	25.1%	20.6%	6.3%	2.1%	2.2%	1.5%	1.6%	1.4%	0.7%
2003	14.3%	9.7%	17.0%	19.5%	10.0%	5.3%	7.1%	4.8%	5.3%	4.5%	2.4%
2004	18.1%	11.9%	20.2%	19.9%	8.5%	4.0%	5.1%	3.5%	3.8%	3.2%	1.7%
2005	21.0%	13.5%	22.5%	20.2%	7.4%	3.1%	3.6%	2.5%	2.7%	2.3%	1.2%
2006	18.5%	11.9%	20.1%	19.8%	8.5%	4.0%	5.0%	3.4%	3.8%	3.2%	1.7%
2007	25.5%	16.5%	27.1%	21.0%	5.4%	1.3%	1.0%	0.7%	0.7%	0.6%	0.3%
Average	23.1%	15.0%	24.8%	20.6%	6.4%	2.2%	2.3%	1.6%	1.8%	1.5%	0.8%

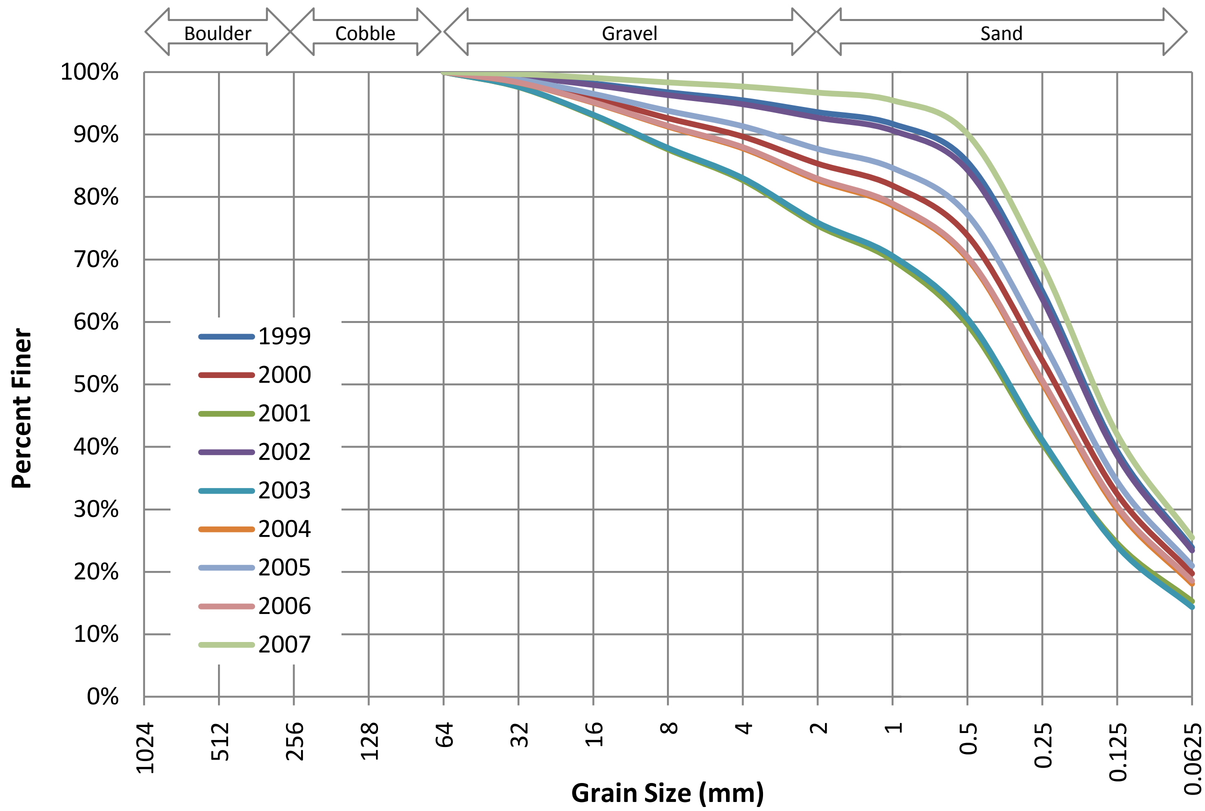

Figure 4.2 Gradation of Toutle Basin Sediment Sources below the SRS for Surrogate Years 1999 to 2007

4.2 Annual Sediment Load at Mouth of Toutle River

Computation of the annual sediment load at the mouth of the Toutle River, used as input to the Cowlitz River models, was conducted by summing the annual sediment output from the SRS and Toutle Basin sediment sources. Annual loads were calculated for the Cowlitz 1-D model calibration time period of WYs 2003 through 2007 and the long-term forecasting sequence of 2008 to 2035.

Annual sediment loads computed for use in the Cowlitz calibration models include WYs 2003 through 2007 and were developed from the sediment budget results, see Table 4.3.

Table 4.3 Calibration Annual Sediment Output from the SRS, Toutle Basin Sources, and Total Load at Mouth of Toutle River, Sediment Budget

Water Year	Sediment Output from the SRS (tons)	Toutle Basin Sources Below the SRS (tons)	Sediment Load at Mouth of Toutle River (tons)
2003	4,638,355	627,855	5,266,210
2004	2,095,756	460,958	2,556,714
2005	2,362,813	466,271	2,829,084
2006	4,675,052	611,511	5,286,563
2007	17,409,420	5,326,686	22,736,105

Three sets of annual sediment loads at the mouth of the Toutle River were developed for long-term Cowlitz sediment transport modeling through 2035 including; 1) full sediment budget results, 2) results of 1-D modeling above the SRS coupled with Toutle Basin sediment sources below the SRS from the Sediment Budget, and 3) results of the 2-D modeling above the SRS also coupled with Toutle Basin sources below the SRS from the Sediment Budget.

The cumulative sediment load at the mouth of the Toutle River through 2035 for all model results is shown graphically in Figure 4.3 and in tabular form in Table 4.4. The cumulative sediment load at the mouth in 2035 computed by the Sediment Budget, 1-D modeling, and 2-D modeling results are 173, 183, 203 M Tons, respectively. Note that the sediment budget results do not account for decay in trapping efficiency of the SRS, resulting in the lowest estimate. Comparison of the 1-D and 2-D results show a difference of approximately 10%.

Of these three approaches, the 2-D model results and computed load to the Cowlitz was selected for use in the downstream long-term runs. While both the 1-D and 2-D approaches account for decay in SRS trapping efficiency and generally agree well with each other, the 2-D model more accurately solves the hydraulics of the complex braided sediment plain. Results from all three approaches are shown to inform the reader on the effect of SRS decay to total sediment load passing the SRS and to provide transparency on the range of calibrated model solutions.

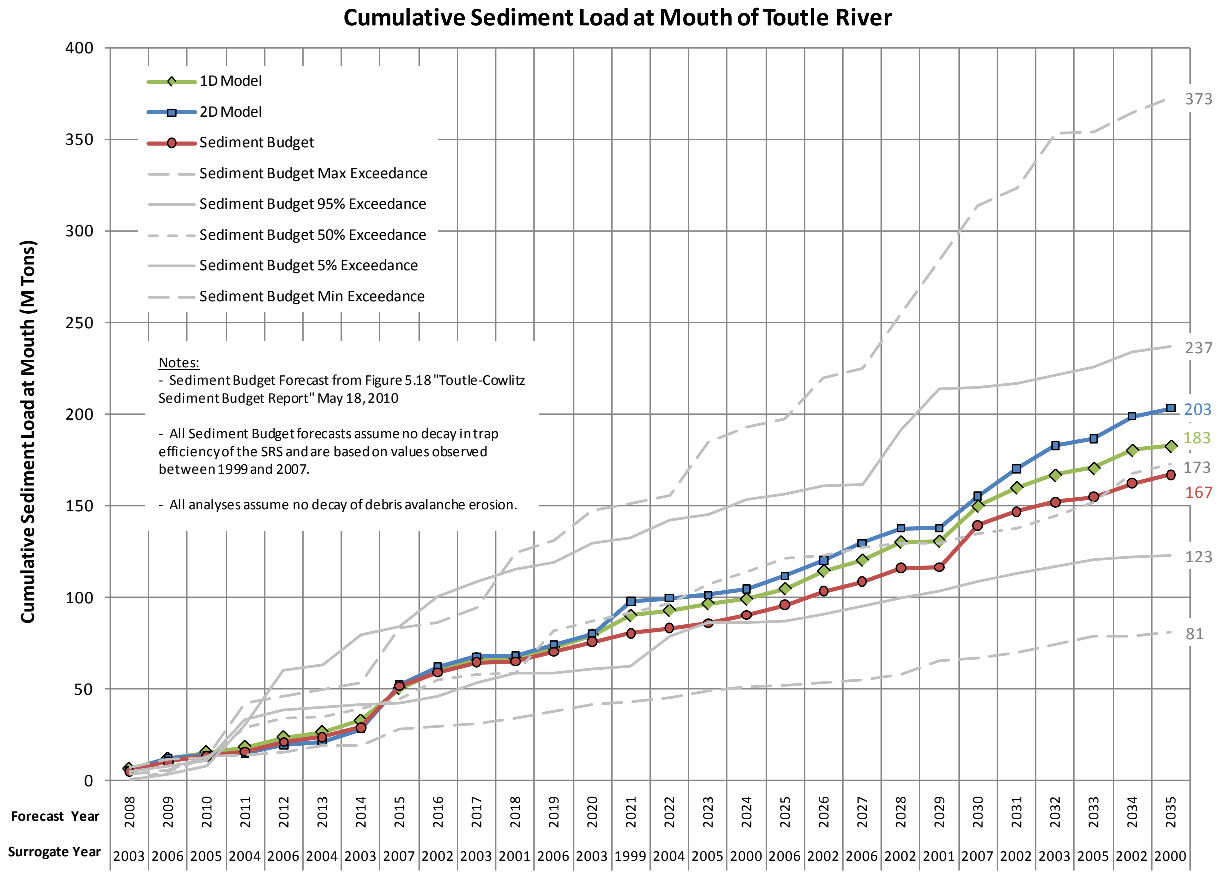

Figure 4.3 Cumulative Sediment Load at the Mouth of the Toutle River through 2035

Table 4.4 Long-term Forecasting Annual Sediment Output from the SRS, Toutle Basin Sources, and Total Load at Mouth of Toutle River

Forecast Year	Surrogate Year	Sediment Output from the SRS (tons)			Toutle Basin Sources Below the SRS (tons)	Sediment Load at Mouth of Toutle River (tons)		
		Sediment Budget	1-D	2-D	Sediment Budget	Sediment Budget	1-D	2-D
2008	2003	4,638,355	5,754,129	5,323,026	627,855	5,266,210	6,381,984	5,950,880
2009	2006	4,675,052	4,961,592	5,874,792	611,511	5,286,563	5,573,103	6,486,303
2010	2005	2,362,813	3,042,344	1,158,300	466,271	2,829,084	3,508,615	1,624,571
2011	2004	2,095,756	2,441,814	751,706	460,958	2,556,714	2,902,772	1,212,664
2012	2006	4,675,052	4,696,361	3,749,477	611,511	5,286,563	5,307,872	4,360,989
2013	2004	2,095,756	2,403,931	1,063,823	460,958	2,556,714	2,864,889	1,524,780
2014	2003	4,638,355	5,547,293	6,265,691	627,855	5,266,210	6,175,148	6,893,547
2015	2007	17,409,420	12,209,084	19,334,080	5,326,686	22,736,105	17,535,770	24,660,766
2016	2002	5,944,320	8,146,583	7,800,680	1,498,276	7,442,596	9,644,859	9,298,957
2017	2003	4,638,355	5,993,410	5,239,814	627,855	5,266,210	6,621,265	5,867,668
2018	2001	546,391	457,035	0	89,142	635,533	546,178	89,142
2019	2006	4,675,052	5,022,760	5,746,881	611,511	5,286,563	5,634,270	6,358,393
2020	2003	4,638,355	5,982,211	5,339,659	627,855	5,266,210	6,610,066	5,967,514
2021	1999	2,843,397	8,769,442	15,506,676	2,035,838	4,879,235	10,805,280	17,542,514
2022	2004	2,095,756	2,432,446	1,411,189	460,958	2,556,714	2,893,404	1,872,147
2023	2005	2,362,813	3,186,350	1,161,204	466,271	2,829,084	3,652,621	1,627,475
2024	2000	3,784,857	1,650,389	2,514,628	766,429	4,551,286	2,416,819	3,281,057
2025	2006	4,675,052	5,069,275	6,530,120	611,511	5,286,563	5,680,785	7,141,631
2026	2002	5,944,320	8,294,822	7,087,142	1,498,276	7,442,596	9,793,098	8,585,419
2027	2006	4,675,052	5,309,342	8,738,417	611,511	5,286,563	5,920,853	9,349,929
2028	2002	5,944,320	8,334,853	6,508,780	1,498,276	7,442,596	9,833,129	8,007,057
2029	2001	546,391	347,536	0	89,142	635,533	436,678	89,142
2030	2007	17,409,420	13,941,871	12,076,782	5,326,686	22,736,105	19,268,556	17,403,467
2031	2002	5,944,320	8,571,489	13,404,151	1,498,276	7,442,596	10,069,765	14,902,427
2032	2003	4,638,355	6,123,712	12,127,731	627,855	5,266,210	6,751,567	12,755,586
2033	2005	2,362,813	3,281,909	3,154,475	466,271	2,829,084	3,748,180	3,620,746
2034	2002	5,944,320	8,381,198	10,719,187	1,498,276	7,442,596	9,879,474	12,217,464
2035	2000	3,784,857	1,461,381	3,736,165	766,429	4,551,286	2,227,810	4,502,594
Total		**135,989,077**	**151,814,561**	**172,324,576**	**30,870,249**	**166,859,326**	**182,684,810**	**203,194,829**

All annual sediment loads were also computed for each grain class. The cumulative sediment load at the mouth of the Toutle River through 2035 for each grain class and model is shown in Figure 4.4. A summary of the total percent of silt/clay, sand, and gravel is provided in Table 4.5. In all three cases, over half the load at the mouth of the Toutle is comprised of sands with very little gravel present. Differences between the 1-D and 2-D modeling results by grain size can be attributed to the computational variations between the models, especially the application of two different sediment transport equations. Detailed breakdowns of the annual sediment loads by grain size for the Sediment Budget, 1-D, and 2-D modeling results are shown in Table 4.6, Table 4.7, and Table 4.8, respectively.

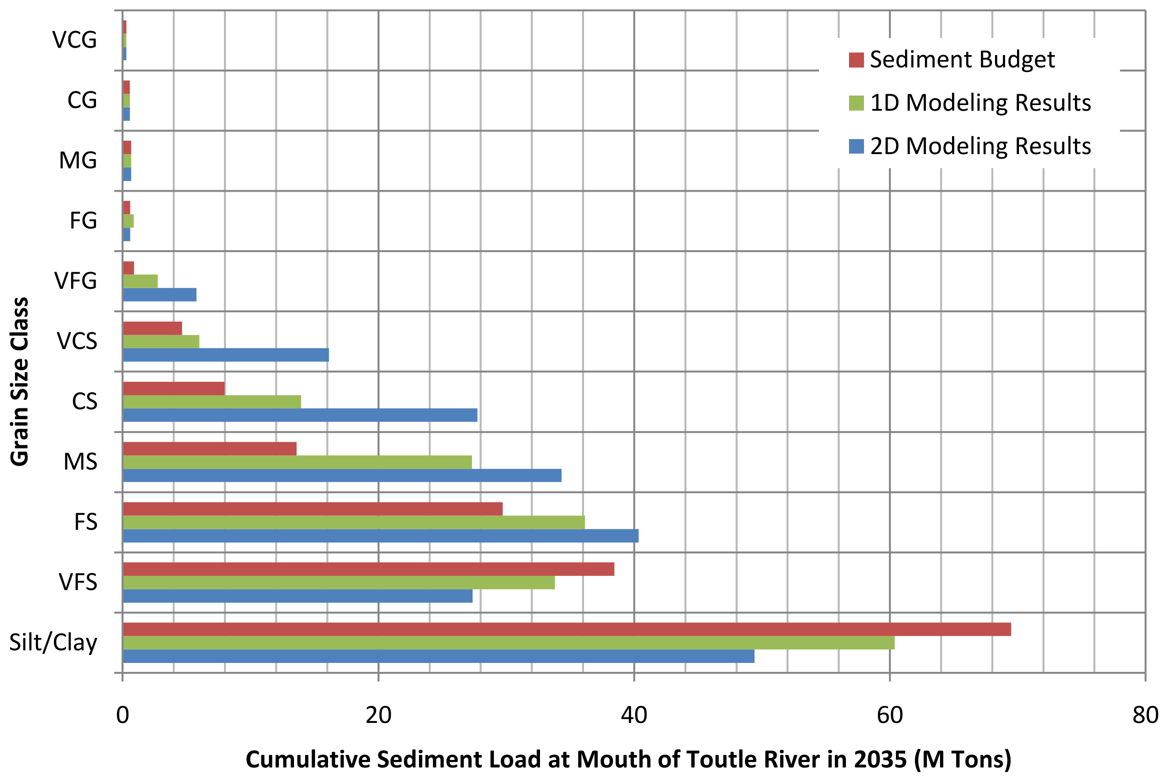

Figure 4.4 Cumulative Sediment Load at Mouth of Toutle River in 2035 by Grain Class

Table 4.5 Overall Breakdown of Type of Sediment Load at Mouth of Toutle River through 2035

	Silt/Clay	Sand	Gravel
Sediment Budget	41.6%	56.6%	1.8%
1-D Results	33.1%	64.2%	2.8%
2-D Results	24.3%	71.8%	3.9%

Table 4.6 Annual Sediment Load at Mouth of Toutle River by Grain Size through 2035 from Sediment Budget Results

		Sediment Budget Results – Annual Sediment Load at Mouth of Toutle (tons)											
Forecast Year	Surrogate Year	Total	Silt/Clay 0.0625	VFS 0.125	FS 0.25	MS 0.5	CS 1	VCS 2	VFG 4	FG 8	MG 16	CG 32	VCG 64
2008	2003	5,266,210	2,368,627	1,258,468	909,847	251,680	199,094	127,048	44,690	30,407	33,485	28,048	14,818
2009	2006	5,286,563	2,148,627	1,200,646	991,573	436,045	256,612	148,645	30,811	20,964	23,086	19,337	10,216
2010	2005	2,829,084	1,300,779	693,906	526,290	136,279	72,750	41,700	16,932	11,521	12,687	10,627	5,614
2011	2004	2,556,714	1,086,039	594,775	411,385	123,150	150,688	110,721	23,594	16,053	17,678	14,808	7,823
2012	2006	5,286,563	2,148,627	1,200,646	991,573	436,045	256,612	148,645	30,811	20,964	23,086	19,337	10,216
2013	2004	2,556,714	1,086,039	594,775	411,385	123,150	150,688	110,721	23,594	16,053	17,678	14,808	7,823
2014	2003	5,266,210	2,368,627	1,258,468	909,847	251,680	199,094	127,048	44,690	30,407	33,485	28,048	14,818
2015	2007	22,736,105	9,213,110	5,052,256	3,655,100	2,567,745	1,365,525	707,407	51,629	35,128	38,684	32,403	17,119
2016	2002	7,442,596	3,297,772	1,770,572	1,400,893	456,810	260,489	146,472	32,338	22,002	24,230	20,296	10,722
2017	2003	5,266,210	2,368,627	1,258,468	909,847	251,680	199,094	127,048	44,690	30,407	33,485	28,048	14,818
2018	2001	635,533	162,309	103,810	117,986	117,392	72,675	39,443	6,468	4,400	4,846	4,059	2,144
2019	2006	5,286,563	2,148,627	1,200,646	991,573	436,045	256,612	148,645	30,811	20,964	23,086	19,337	10,216
2020	2003	5,266,210	2,368,627	1,258,468	909,847	251,680	199,094	127,048	44,690	30,407	33,485	28,048	14,818
2021	1999	4,879,235	2,235,038	1,093,342	836,010	421,691	124,203	38,199	38,583	26,252	28,909	24,215	12,793
2022	2004	2,556,714	1,086,039	594,775	411,385	123,150	150,688	110,721	23,594	16,053	17,678	14,808	7,823
2023	2005	2,829,084	1,300,779	693,906	526,290	136,279	72,750	41,700	16,932	11,521	12,687	10,627	5,614
2024	2000	4,551,286	1,128,887	1,017,803	1,004,001	656,656	358,130	273,400	33,170	22,569	24,853	20,818	10,998
2025	2006	5,286,563	2,148,627	1,200,646	991,573	436,045	256,612	148,645	30,811	20,964	23,086	19,337	10,216
2026	2002	7,442,596	3,297,772	1,770,572	1,400,893	456,810	260,489	146,472	32,338	22,002	24,230	20,296	10,722
2027	2006	5,286,563	2,148,627	1,200,646	991,573	436,045	256,612	148,645	30,811	20,964	23,086	19,337	10,216
2028	2002	7,442,596	3,297,772	1,770,572	1,400,893	456,810	260,489	146,472	32,338	22,002	24,230	20,296	10,722
2029	2001	635,533	162,309	103,810	117,986	117,392	72,675	39,443	6,468	4,400	4,846	4,059	2,144
2030	2007	22,736,105	9,213,110	5,052,256	3,655,100	2,567,745	1,365,525	707,407	51,629	35,128	38,684	32,403	17,119
2031	2002	7,442,596	3,297,772	1,770,572	1,400,893	456,810	260,489	146,472	32,338	22,002	24,230	20,296	10,722
2032	2003	5,266,210	2,368,627	1,258,468	909,847	251,680	199,094	127,048	44,690	30,407	33,485	28,048	14,818
2033	2005	2,829,084	1,300,779	693,906	526,290	136,279	72,750	41,700	16,932	11,521	12,687	10,627	5,614
2034	2002	7,442,596	3,297,772	1,770,572	1,400,893	456,810	260,489	146,472	32,338	22,002	24,230	20,296	10,722
2035	2000	4,551,286	1,128,887	1,017,803	1,004,001	656,656	358,130	273,400	33,170	22,569	24,853	20,818	10,998
Total		**166,859,326**	**69,479,232**	**38,455,551**	**29,714,775**	**13,606,241**	**7,968,154**	**4,646,788**	**881,890**	**600,033**	**660,769**	**553,485**	**292,407**

[A] VFS = very fine sand, FS = fine sand, MS = medium sand, CS = coarse sand, VCS = very coarse sand, VFG = very fine gravel, FG = fine gravel, MG = medium gravel, CG = coarse gravel; VCG = very coarse gravel

Table 4.7 Annual Sediment Load at Mouth of Toutle River by Grain Size through 2035 from 1-D Model Results

		1-D Model Results – Annual Sediment Load at Mouth of Toutle (tons)											
Forecast Year	**Surrogate Year**	**Total**	**Silt/Clay 0.0625**	**VFS 0.125**	**FS 0.25**	**MS 0.5**	**CS 1**	**VCS 2**	**VFG 4**	**FG 8**	**MG 16**	**CG 32**	**VCG 64**
2008	2003	6,381,984	2,112,119	1,461,249	1,433,951	877,834	283,505	61,300	45,217	30,459	33,485	28,048	14,818
2009	2006	5,573,103	1,859,954	868,932	1,108,105	916,585	519,476	192,949	33,424	21,037	23,088	19,337	10,216
2010	2005	3,508,615	1,393,013	624,591	652,961	437,653	221,854	101,624	36,459	11,531	12,687	10,627	5,614
2011	2004	2,902,772	1,080,866	483,475	530,753	369,037	218,842	111,509	51,915	16,067	17,678	14,808	7,823
2012	2006	5,307,872	1,859,079	865,479	1,038,740	765,853	438,755	177,220	89,055	21,052	23,086	19,337	10,216
2013	2004	2,864,889	1,080,366	484,353	533,824	356,738	184,910	106,927	61,393	16,070	17,678	14,808	7,823
2014	2003	6,175,148	2,078,899	1,392,002	1,267,151	784,548	351,844	112,273	81,600	30,481	33,486	28,048	14,818
2015	2007	17,535,770	5,879,155	4,330,197	3,779,173	2,394,906	748,995	203,085	76,834	35,217	38,687	32,403	17,119
2016	2002	9,644,859	3,331,244	1,583,752	1,922,413	1,563,002	829,287	284,511	53,389	22,014	24,230	20,296	10,722
2017	2003	6,621,265	2,081,683	1,392,169	1,301,112	896,502	500,749	237,870	104,382	30,449	33,485	28,048	14,818
2018	2001	546,178	142,929	55,423	75,343	80,968	78,690	80,441	16,934	4,400	4,846	4,059	2,144
2019	2006	5,634,270	1,857,222	866,960	1,104,639	918,430	476,839	207,736	128,678	21,127	23,086	19,337	10,216
2020	2003	6,610,066	2,079,739	1,396,659	1,276,166	881,745	507,670	233,605	126,323	31,809	33,485	28,048	14,818
2021	1999	10,805,280	3,365,536	1,781,662	2,137,401	1,777,846	956,582	452,799	222,913	44,623	28,910	24,215	12,793
2022	2004	2,893,404	1,080,591	484,631	536,169	369,359	206,777	95,827	61,245	18,496	17,678	14,808	7,823
2023	2005	3,652,621	1,391,766	624,398	656,236	481,416	277,480	125,412	51,861	15,123	12,687	10,627	5,614
2024	2000	2,416,819	594,842	280,608	420,481	427,822	287,951	184,811	123,236	40,397	24,854	20,818	10,998
2025	2006	5,680,785	1,856,996	871,890	1,127,189	925,429	483,276	213,012	94,980	55,373	23,086	19,337	10,216
2026	2002	9,793,098	3,324,345	1,558,645	1,833,429	1,535,938	879,989	391,963	160,565	52,976	24,230	20,296	10,722
2027	2006	5,920,853	1,861,370	868,840	1,119,139	972,959	570,017	294,200	138,816	42,872	23,087	19,337	10,216
2028	2002	9,833,129	3,324,405	1,557,895	1,835,079	1,558,758	887,791	390,371	178,377	45,207	24,230	20,296	10,722
2029	2001	436,678	143,906	52,513	60,723	53,594	42,817	34,902	32,367	4,807	4,846	4,059	2,144
2030	2007	19,268,556	5,878,288	4,459,707	4,275,334	2,979,729	1,068,047	322,293	130,465	66,486	38,687	32,403	17,119
2031	2002	10,069,765	3,330,540	1,569,585	1,885,259	1,613,188	969,895	442,384	165,055	38,612	24,230	20,296	10,722
2032	2003	6,751,567	2,082,428	1,407,899	1,341,156	948,581	517,988	227,384	110,649	39,133	33,485	28,048	14,818
2033	2005	3,748,180	1,393,355	625,318	665,166	495,986	300,639	151,193	72,026	15,568	12,687	10,627	5,614
2034	2002	9,879,474	3,325,349	1,563,365	1,852,109	1,556,888	901,777	409,728	167,195	47,815	24,231	20,296	10,722
2035	2000	2,227,810	594,971	274,118	386,981	369,572	230,841	151,772	127,236	35,648	24,854	20,818	10,998
Total		**182,684,810**	**60,384,958**	**33,786,308**	**36,156,179**	**27,310,864**	**13,943,284**	**5,999,099**	**2,742,590**	**854,848**	**660,787**	**553,485**	**292,407**

Table 4.8 Annual Sediment Load at Mouth of Toutle River by Grain Size through 2035 from 2-D Model Results

2-D Model Results – Annual Sediment Load at Mouth of Toutle (tons)													
Forecast Year	**Surrogate Year**	**Total**	**Silt/Clay 0.0625**	**VFS 0.125**	**FS 0.25**	**MS 0.5**	**CS 1**	**VCS 2**	**VFG 4**	**FG 8**	**MG 16**	**CG 32**	**VCG 64**
2008	2003	5,950,880	2,295,449	1,248,688	1,530,611	511,981	128,811	66,577	62,007	30,407	33,485	28,048	14,818
2009	2006	6,486,303	2,216,882	1,205,558	1,449,836	1,160,513	235,774	78,739	65,398	20,964	23,086	19,337	10,216
2010	2005	1,624,571	562,308	313,079	327,952	234,501	92,648	23,763	29,871	11,521	12,687	10,627	5,614
2011	2004	1,212,664	345,555	196,120	222,526	204,225	121,389	33,897	32,590	16,053	17,678	14,808	7,823
2012	2006	4,360,989	1,156,885	634,791	960,257	924,105	469,288	82,855	59,205	20,964	23,086	19,337	10,216
2013	2004	1,524,780	346,202	196,469	295,225	339,832	228,997	32,334	29,359	16,053	17,678	14,808	7,823
2014	2003	6,893,547	2,449,866	1,331,835	947,619	1,058,864	718,621	199,814	80,172	30,407	33,485	28,048	14,818
2015	2007	24,660,766	7,189,665	4,019,831	6,354,907	4,280,304	1,928,565	641,653	122,507	35,128	38,684	32,403	17,119
2016	2002	9,298,957	2,059,784	1,147,524	1,651,105	1,921,991	1,676,763	683,012	81,529	22,002	24,230	20,296	10,722
2017	2003	5,867,668	1,271,934	697,564	1,367,257	1,087,553	807,290	435,289	94,025	30,407	33,485	28,048	14,818
2018	2001	89,142	13,604	8,293	14,233	16,964	9,192	4,939	6,468	4,400	4,846	4,059	2,144
2019	2006	6,358,393	1,212,812	664,906	905,172	1,392,502	1,365,223	636,759	107,416	20,964	23,086	19,337	10,216
2020	2003	5,967,514	1,154,357	634,254	1,110,680	1,255,774	993,756	625,338	86,600	30,407	33,485	28,048	14,818
2021	1999	17,542,514	3,796,933	2,097,819	3,190,963	2,619,144	3,200,189	2,298,628	246,668	26,252	28,909	24,215	12,793
2022	2004	1,872,147	462,336	259,002	295,059	279,316	267,549	187,671	64,852	16,053	17,678	14,808	7,823
2023	2005	1,627,475	378,007	213,840	349,370	263,332	174,374	152,125	55,978	11,521	12,687	10,627	5,614
2024	2000	3,281,057	687,638	386,439	346,621	348,273	714,394	541,832	176,621	22,569	24,853	20,818	10,998
2025	2006	7,141,631	1,484,930	811,431	1,751,548	1,179,188	818,397	695,227	327,307	20,964	23,086	19,337	10,216
2026	2002	8,585,419	1,827,415	1,022,402	1,772,400	1,610,355	1,231,951	635,451	408,196	22,002	24,230	20,296	10,722
2027	2006	9,349,929	1,784,684	972,837	1,672,665	1,736,355	1,699,637	1,007,594	402,554	20,964	23,086	19,337	10,216
2028	2002	8,007,057	1,758,221	985,144	1,495,621	1,357,940	1,162,307	876,010	294,565	22,002	24,230	20,296	10,722
2029	2001	89,142	13,604	8,293	14,233	16,964	9,192	4,939	6,468	4,400	4,846	4,059	2,144
2030	2007	17,403,467	4,267,535	2,446,377	4,705,713	3,103,799	1,615,006	837,622	304,081	35,128	38,684	32,403	17,119
2031	2002	14,902,427	2,863,604	1,580,350	2,433,227	2,882,852	2,794,264	1,673,372	597,509	22,002	24,230	20,296	10,722
2032	2003	12,755,586	3,812,466	2,065,543	2,396,002	1,652,342	1,507,461	872,264	342,752	30,407	33,485	28,048	14,818
2033	2005	3,620,746	776,527	428,428	449,315	550,511	738,068	435,806	201,642	11,521	12,687	10,627	5,614
2034	2002	12,217,464	2,525,730	1,398,418	1,973,524	1,881,369	2,063,546	1,498,095	799,533	22,002	24,230	20,296	10,722
2035	2000	4,502,594	706,747	396,728	375,506	442,348	964,341	866,786	670,899	22,569	24,853	20,818	10,998
Total		**203,194,829**	**49,421,681**	**27,371,960**	**40,359,144**	**34,313,195**	**27,736,995**	**16,128,388**	**5,756,772**	**600,033**	**660,769**	**553,485**	**292,407**

4.3 Development of Daily Sediment Series/Input to Cowlitz River Model

The annual sediment load computed at the mouth of the Toutle River was further disaggregated into a daily time series by grain size for input to Cowlitz River sediment transport models. Disaggregation of annual values was modeled after USGS daily suspended sediment data collected on the Toutle River at Tower Road.

4.3.1 USGS Gage Data Toutle River at Tower Road

Suspended sediment data at the USGS Toutle River at Tower Road Gage No. 14242580 are the most comprehensive data set collected in the Toutle/Cowlitz Basin. Daily suspended sediment records have been collected since the early 1980s. Plots of suspended sediment concentration and suspended sediment discharge vs. discharge measured between 1999 and 2007 are shown in Figure 4.5 and Figure 4.6, respectively. Unmeasured loads are estimated at 25% (Simon 1999). The measured daily sediment time series for WYs 1999 through 2007 (surrogate years) is provided in Figure 4.7.

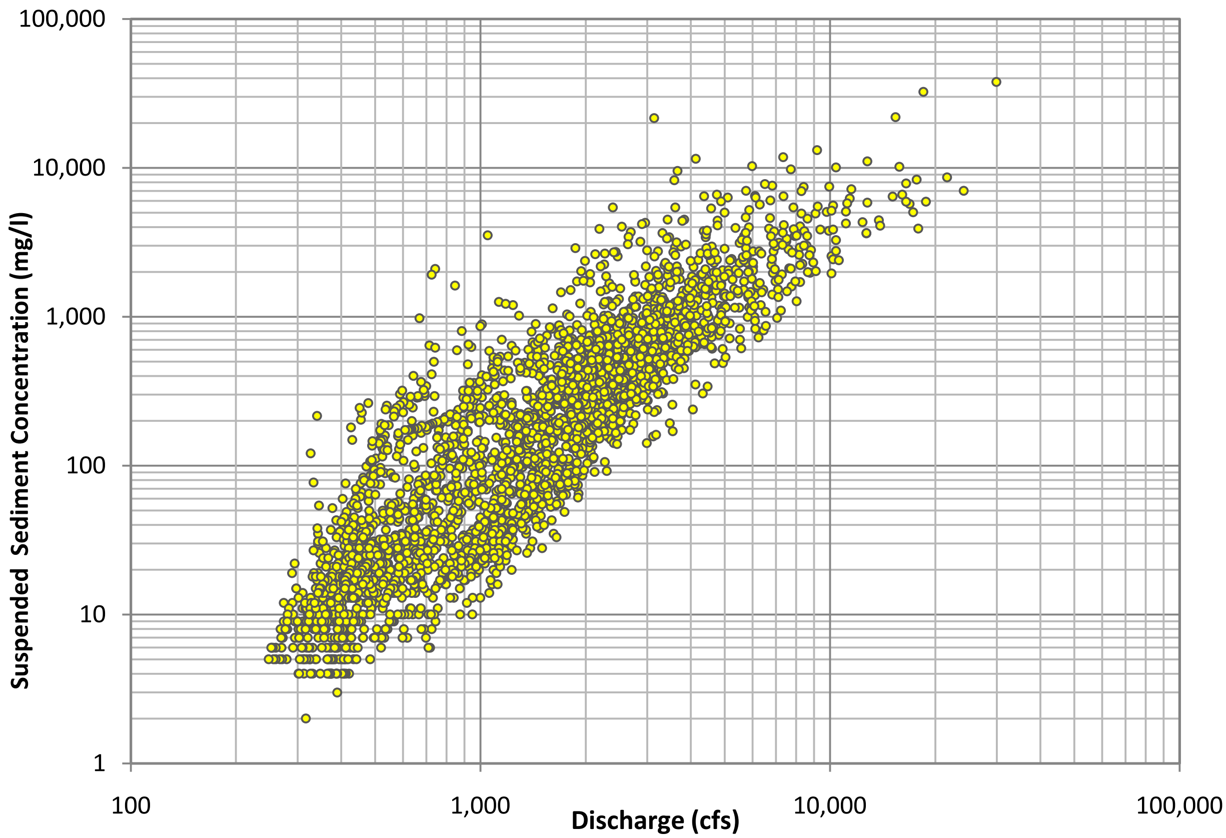

Figure 4.5 Suspended Sediment Concentration vs. Discharge, Toutle at Tower Road Gage, 1999 to 2007

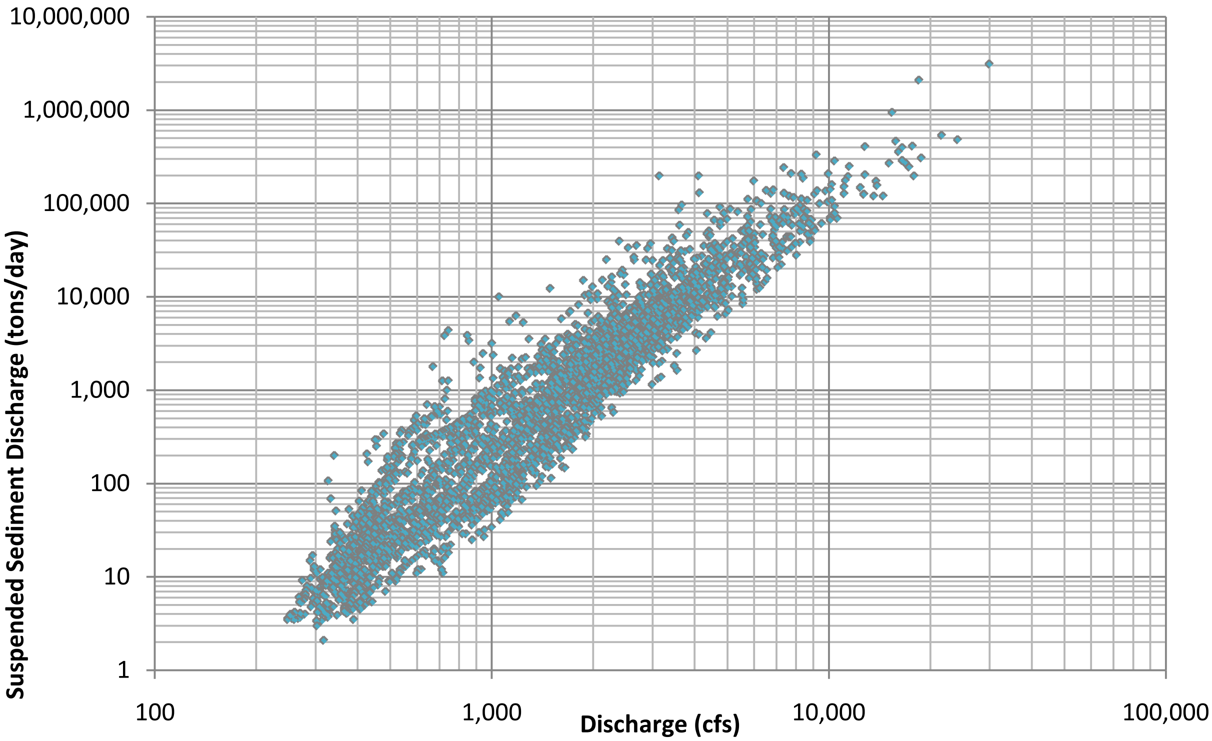

Figure 4.6 Suspended Sediment Discharge vs. Discharge, Toutle at Tower Road Gage, 1999 to 2007

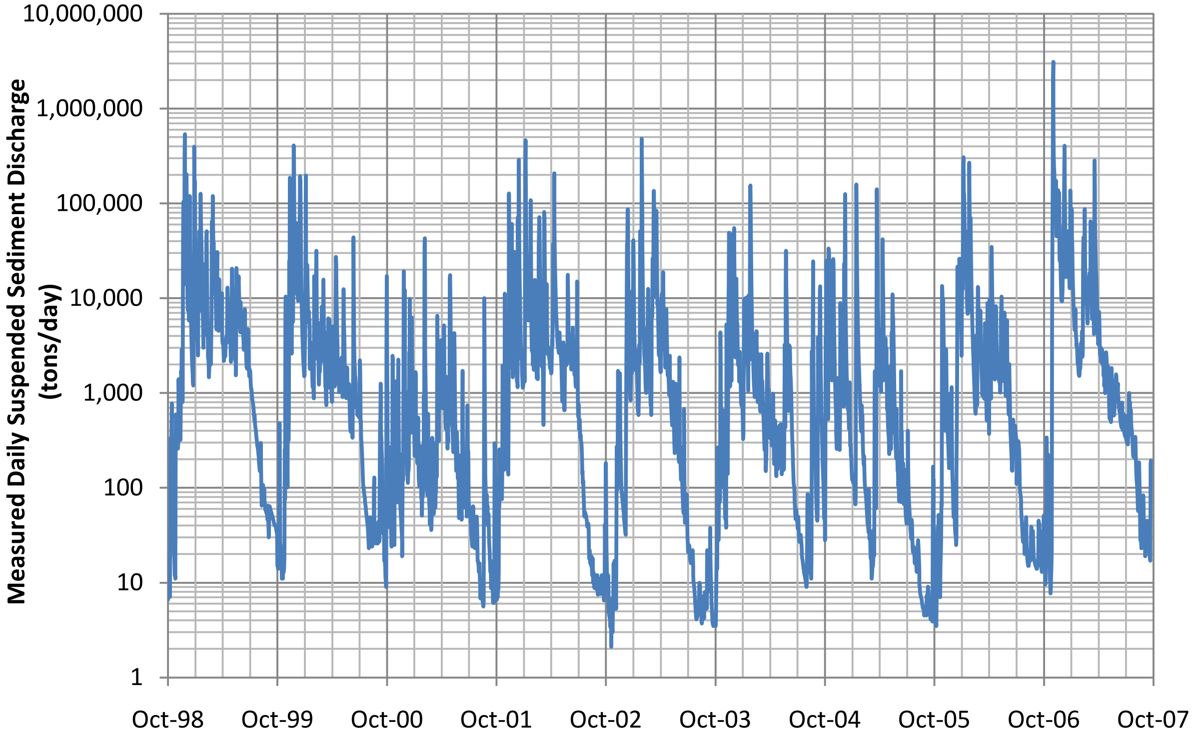

Figure 4.7 Measured Daily Suspended Sediment Discharge, Toutle at Tower Road, WYs 1999 to 2007 (surrogate years)

4.3.2 Daily Sediment Load at Mouth of Toutle River

Results of modeling conducted above the SRS were combined annually with sediment budget sources estimated between the SRS and mouth of the Toutle River. Annual values were then disaggregated into daily time series by pro-rating the annual values by the percentage of daily suspended sediment measured for a given surrogate year. This was conducted for both the calibration period of 2003 to 2007 and the long-term forecasting. Pro-rating of annual values based on daily trends allows for direct use of sediment load time series with historic Toutle River hydrology for use in Cowlitz River models. This was found to be the most efficient way of predicting daily loads without developing sediment transport models of the Toutle system.

The daily and cumulative sediment loads at the mouth of the Toutle computed for the calibration period are shown graphically in Figure 4.8. Sediment budget model results were used for the calibration series. A comparison plot of sediment load vs. discharge of the gage data and load computed at the mouth for the calibration period is shown in Figure 4.9.

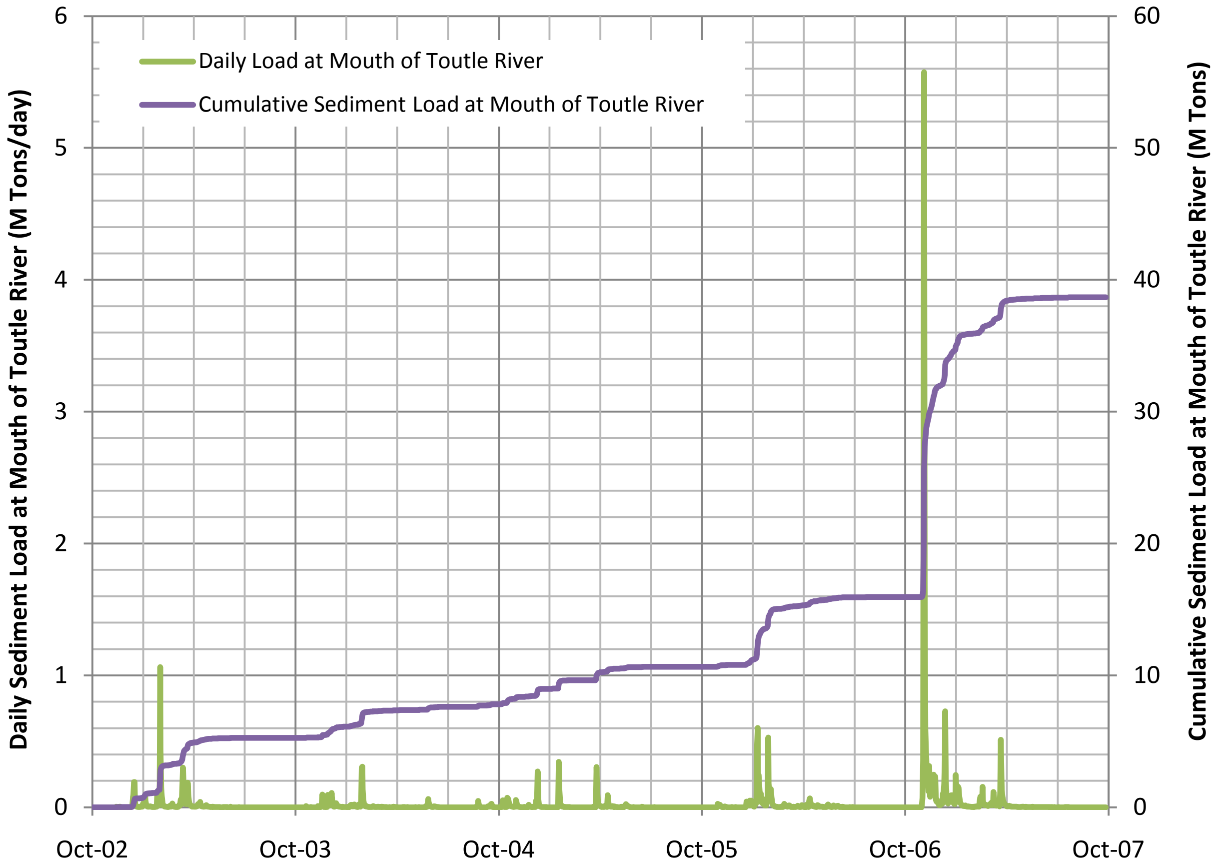

Figure 4.8 Daily and Cumulative Sediment Loads at Mouth of Toutle River Computed Using Sediment Budget Results, Calibration Period 2003 to 2007

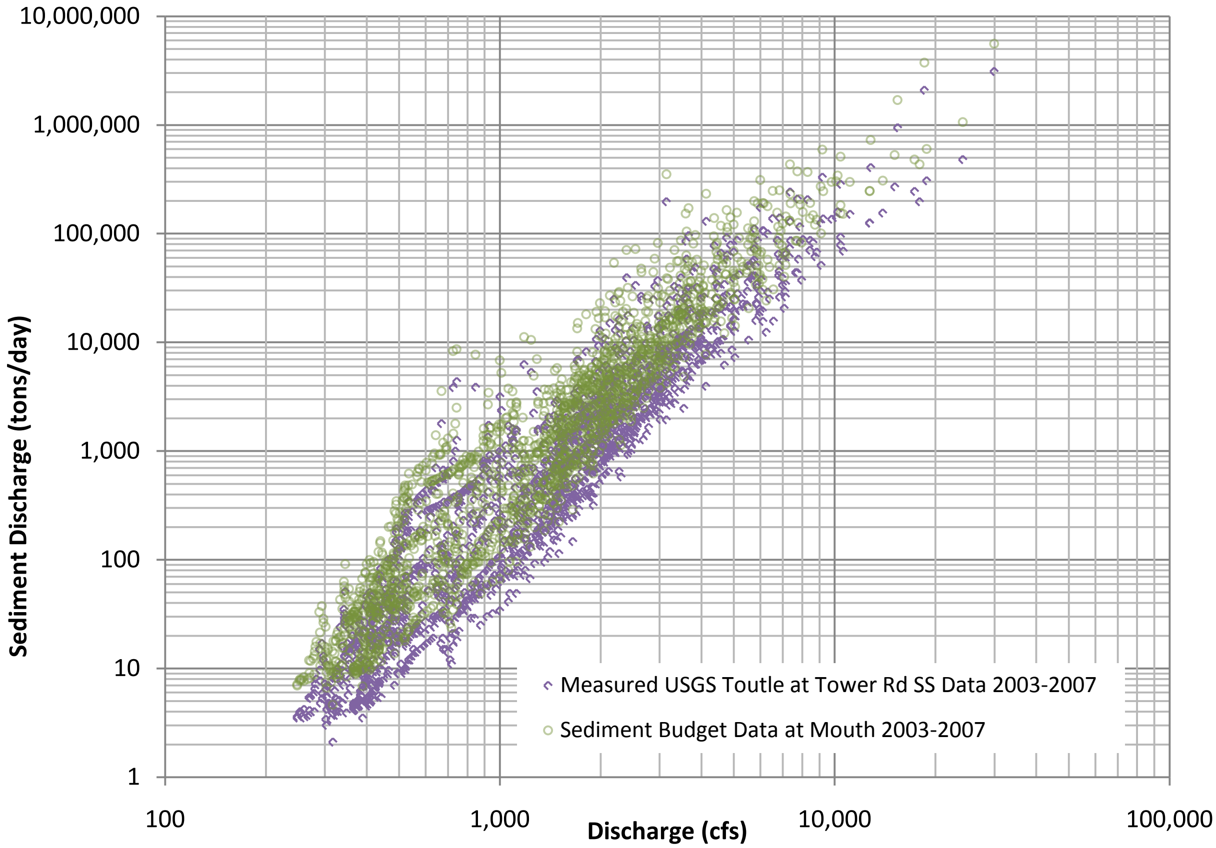

Figure 4.9 Comparison of Measured USGS Suspended Sediment vs. Discharge and Sediment Load at Mouth of Toutle River Computed Sediment Budget vs. Discharge, Calibration Period 2003 to 2007

The daily and cumulative sediment loads at the mouth of the Toutle computed for the long-term forecasting is shown graphically in Figure 4.10. A comparison plot of sediment load vs. discharge of the gage data and load computed at the mouth for the calibration period is shown in Figure 4.11.

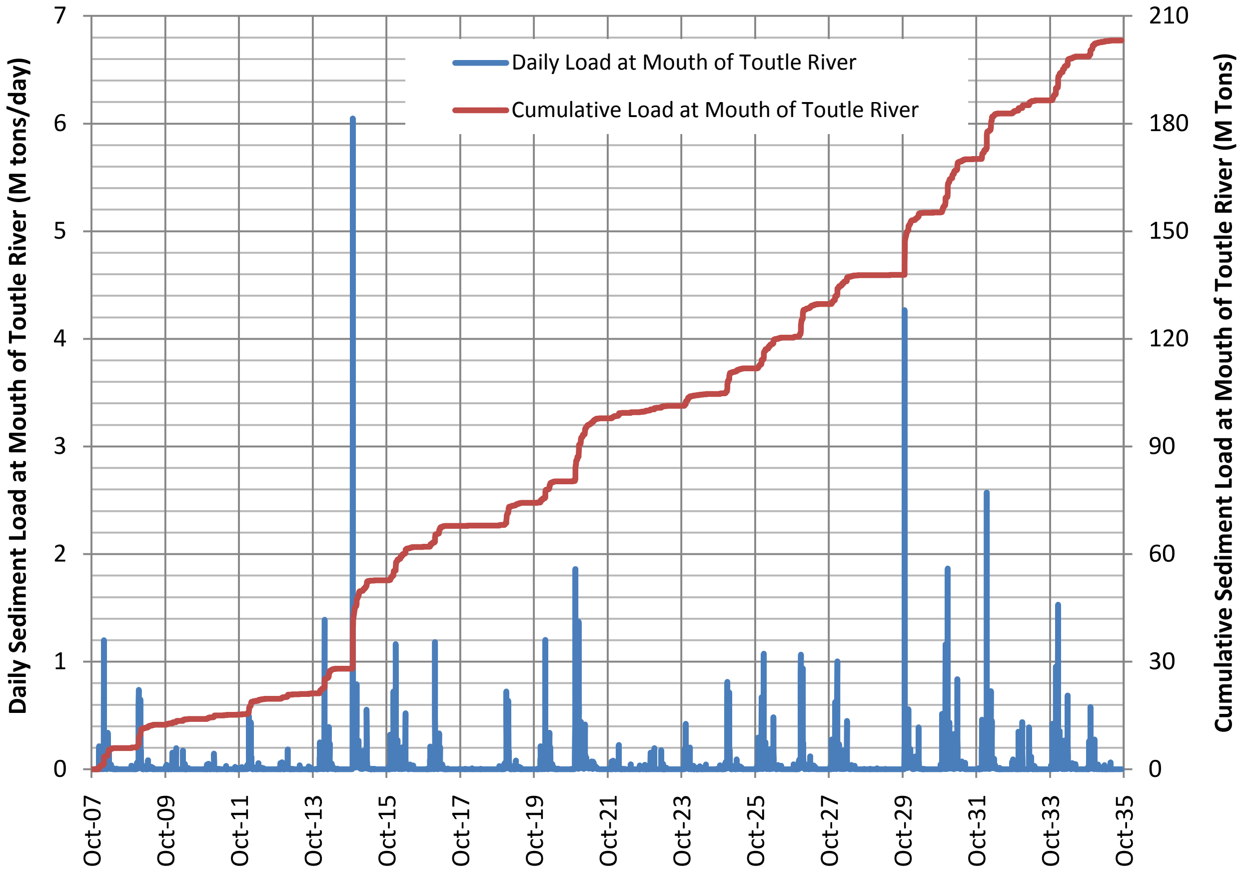

Figure 4.10 Daily and Cumulative Sediment Loads at Mouth of Toutle River Computed Using 2-D Modeling Results, Long-term Forecast through 2035

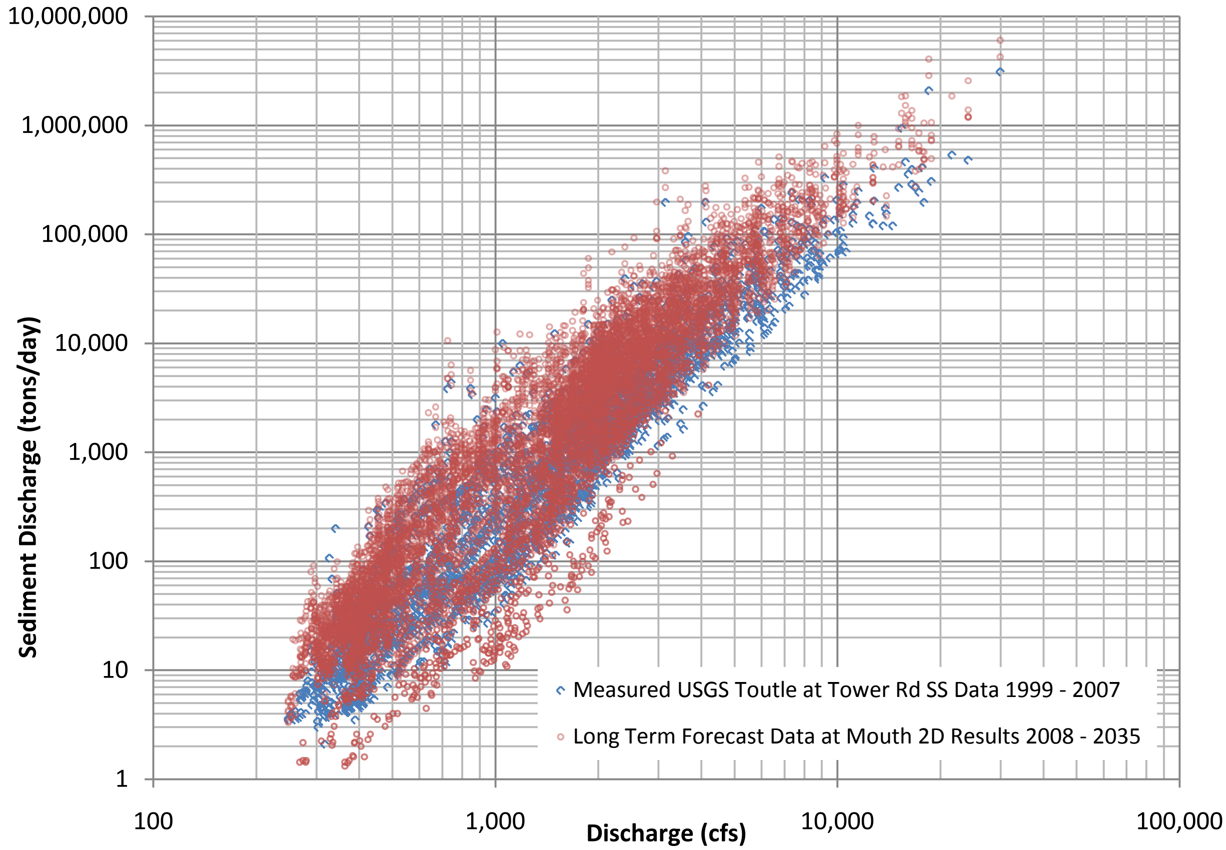

Figure 4.11 Comparison of Measured USGS Suspended Sediment vs. Discharge for Surrogate Years 1999 to 2007 and Sediment Load at Mouth of Toutle River Computed from 2-D Model Results vs. Discharge for the Forecast Period, Calibration Period 2008 to 2035

5.0 COWLITZ RIVER

Three mobile-bed sediment transport models are presented in this section: 1) a 1-D calibration model; 2) a 1-D long-term forecast model; and 3) a 2-D model. The 1-D models are for the lower 20 miles of the Cowlitz River and the 2-D model covers the lower 5 miles.

5.1 Cowlitz River 1-D Hydraulic and Sediment Transport Model

5.1.1 Model Setup

Sediment transport modeling of the Lower Cowlitz River utilized the updated (Beta) Version 4.1 of the USACE's HEC-RAS software. Additional capability was added by the HEC to accommodate particular needs of the sediment transport analysis of the Lower Cowlitz River. These additions are discussed in more detail in the following sections. Cross-section data used to describe the river geometry was obtained from a combination of 2009 LiDAR surveys, 2009 bathymetric surveys, and field investigations. Measured high water marks and gaged stage data from a hydrologic event in January 2009 were used to calibrate the fixed-bed model, specifically the Manning's *n* roughness coefficients. The calibrated fixed-bed model was developed for the 2009 evaluation of the level of protection (LOP) for the levees adjacent the Lower Cowlitz River. The steady-state 1-D fixed-bed hydraulic model utilized 101 cross sections and seven river crossings to describe the lower 20 miles of the Cowlitz River. Details of the development and calibration of this steady-state model can be found in the 2009 LOP study (USACE 2009b) for the levees in the Lower Cowlitz River system. Figure 5.1 shows a cross-section layout of the Lower Cowlitz River hydraulic model.

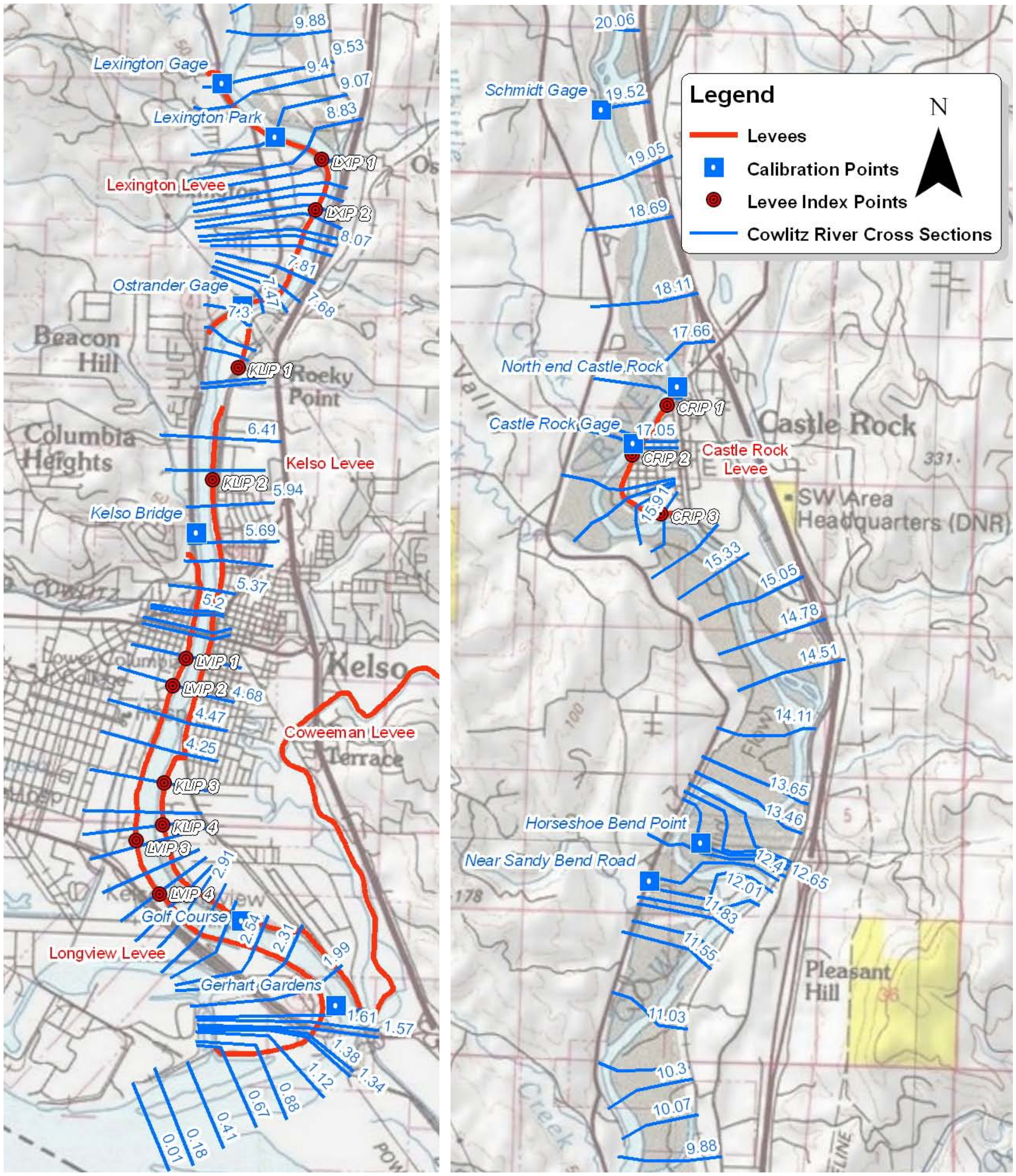

Figure 5.1 Hydraulic Work Map of the Lower Cowlitz Model (from the 2009 LOP Report (USACE 2009b))

While the fixed-bed model from the 2009 LOP evaluation was hydraulically calibrated to the 2009 storm event, the mobile-bed computation required a separate calibration effort. Calibration of the mobile-bed model generally involved adjusting the sediment transport equation within the model until the resulting deposition matched a known depositional volume. The known depositional volume was computed using a series of cross-section surveys taken from 2003 to 2009. Numerical parameters such as the bed exchange iterations variable (also

known as the SPI factor in HEC-6), the Computation Increment (CI), and the cross-section averaging of results were not used for calibration purposes. A sensitivity analysis for the computational parameters provided insight in choosing appropriate values. Development of the mobile-bed model as well as details of the calibration process and selection of specific computation parameters are included in the following sections.

5.1.1.1 Bed gradation

Definition of the bed gradation data within the Sediment Data module of the HEC-RAS software was based on a series of seventeen bed material samples taken along the lower 20 miles of the Cowlitz River in 2005. Figure 5.2 illustrates the locations of these samples.

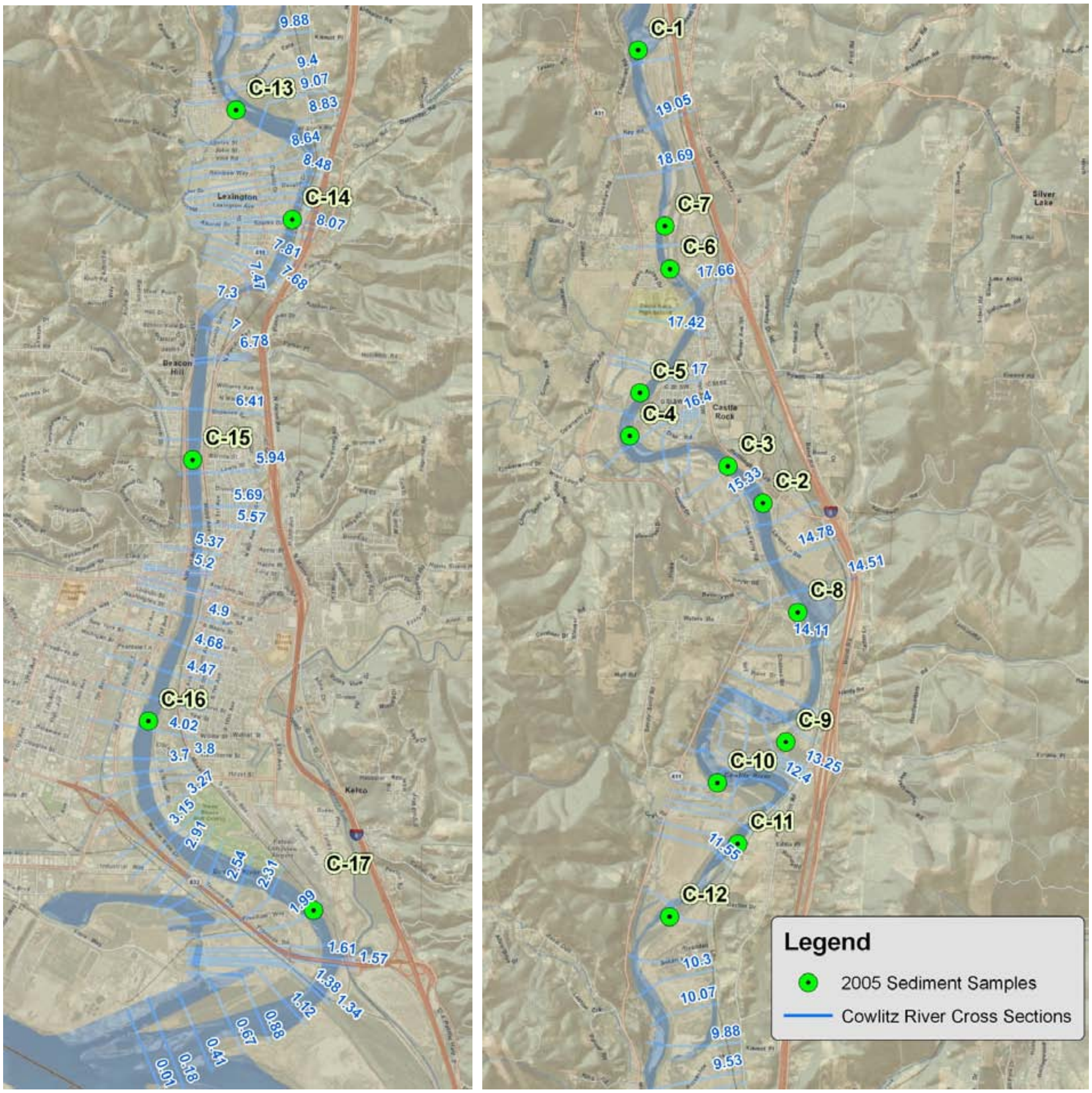

Figure 5.2 Location of Sediment Samples taken in 2005 – These Data were the Basis for Bed Gradation in HEC-RAS Sediment Transport Model of the Lower Cowlitz River

Of the samples shown in Figure 5.2, only seven were used directly to describe distinct reaches of the Lower Cowlitz River. Table 5.1 shows the gradation of the samples along with the reach the specific sample characterizes.

Table 5.1 Gradation of the Samples Used in Characterizing the reaches of the Lower Cowlitz River

Class [A]		Diameter (mm)	C-17 RM 0 to 1.3	C-16 RM 1.5 to 5	C-15 RM 5.1 to 7.5	C-13 RM 7.7 to 10.3	C-12 RM 10.4 to 14.6	C-3 RM 15.1 to 17.4	C-1 RM 17.7 to 20.0
4	MM	0.032				0.01	0.01		0.01
5	CM	0.0625	0.01	0.01	0.1	0.5	1.3	0.4	0.2
6	VFS	0.125	1.4	1.1	0.4	1.4	6.9	1.8	1.3
7	FS	0.25	5.7	21.7	1.6	3.6	17.2	6.5	4.1
8	MS	0.5	47.9	62.5	28.2	25.1	28.8	13.8	6.7
9	CS	1	86.5	93.2	82.1	41.9	35.2	25.5	8.8
10	VCS	2	95	99.5	97.2	55.1	39.1	33.7	13.8
11	VFG	4	97.3	100	99.2	63.4	42.8	37.9	17.8
12	FG	8	99		100	73.8	50	44.9	24.1
13	MG	16	99.6			87	61.6	58.9	34.6
14	CG	32	99.6			98.4	74.1	81.2	54
15	VCG	64	100			100	100	100	90.4
16	SC	128	100						100
	D_{50}		0.5	0.4	0.7	1.5	8.0	10.3	27.7
	D_{90}		1.3	0.9	1.4	19.2	49.0	44.3	63.5
	D_{10}		0.3	0.2	0.3	0.3			

[A] MM = clay, CM = silt, VFS = very fine sand, FS = fine sand, MS = medium sand, CS = coarse sand, VCS = very coarse sand, VFG = very fine gravel, FG = fine gravel, MG = medium gravel, CG = coarse gravel, VCG = very coarse gravel, SC = small cobble

The D_{50} of each sample, also computed in Table 5.1, increases from 1.3 mm at the downstream-most reach to 63.5 mm at the upstream end of the sediment transport model. The most significant shift to coarser material occurs at RMs 10.4 to 14.6. Figure 5.3 shows the D_{10}, D_{50}, and D_{90} from RM 0 to RM 20.0.

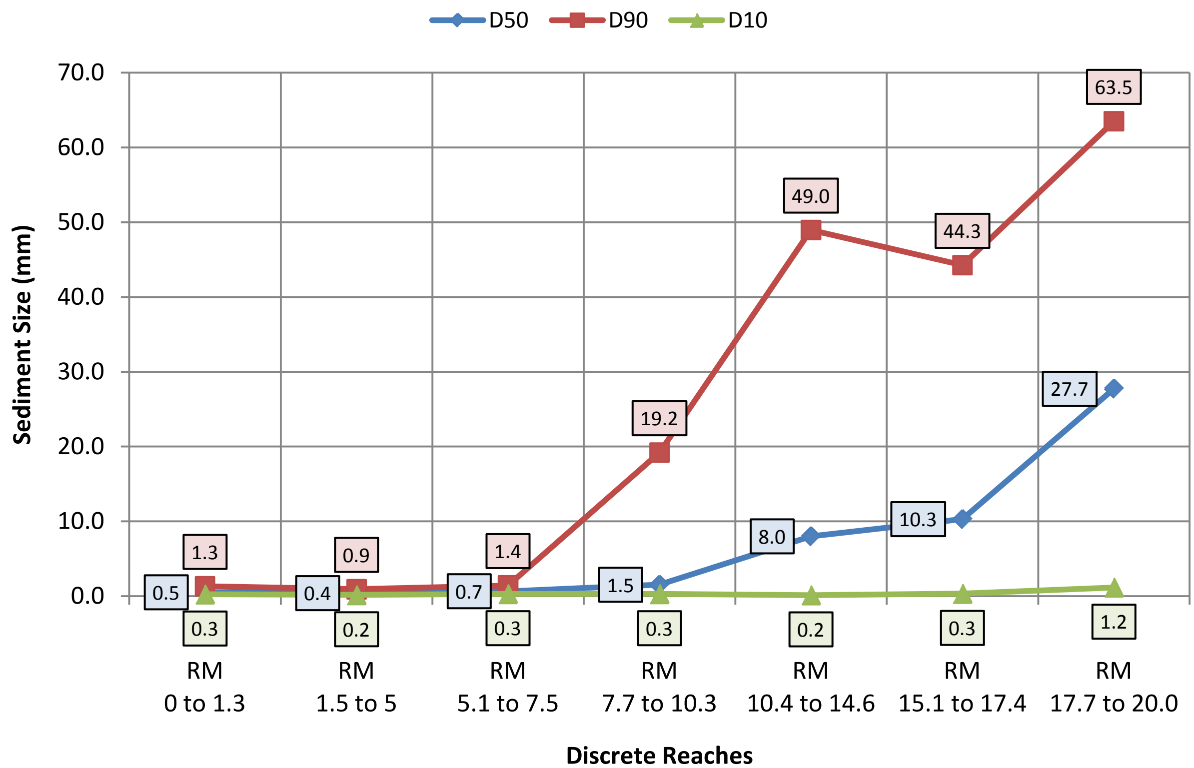

Figure 5.3 Cowlitz River Bed Material D_{10}, D_{50}, and D_{90} by Reach

Based on D_{50}, the lower 10.4 miles of the Cowlitz River consists mainly of coarse sand and finer, while above RM 10.4 the gradation of the bed material shift to gravel. At the upstream end of the model, RM 20.0, the D_{90} was sampled to be 63.5 mm which indicates small cobble size fractions. The D_{10}, also plotted on Figure 5.3, shows medium sand up to about RM 17.7 where the D_{10} coarsens to very coarse sand.

5.1.1.2 Bed exchange iterations

The bed exchange iterations variable also known as the SPI factor in HEC-6 was investigated as a potential calibration parameter. SPI specifies the number of times during a computational time step the composition of the bed material is recalculated. A series of nine HEC-RAS runs were performed with varying SPI ranging from 10 to 500. While guidance indicates that SPI range is limited to 1 to 50, the model was tested outside of this range as the parameter is described as being computationally expensive yet converging at high values. Results indicated that the model is mildly sensitive to moderate ranges of SPI and becomes increasingly sensitive as SPI gets very large. Lower SPI generally resulted in more stable cross-section geometry. Model runs with high SPI rapidly eroded to the set erosional limits in the lower 5 miles resulting in anomalous cross sections that could be problematic for longer run times. An SPI of 10 was selected for all subsequent model runs.

5.1.1.3 Computational interval selection

Assessment of the suitability of a computation interval was made using nine different combinations of computation intervals with a coarser interval for lower flow and finer computation interval for larger flow. Based on cumulative volume change output for six sections over a 6-year period, no discernable trend was noted for the various computational intervals. Cross-section geometry change over time was evaluated to determine which series of computational intervals produced the least amount of perfunctory anomalies, while maintaining satisfactory run times. Table 5.2 shows the nine computational intervals tested along with the selected set of computational intervals.

Table 5.2 Variation of Computational Intervals Tested

Discharge (cfs) [A]		Test Run									Selected
Lower	Upper	0	1	2	3	4	5	6	7	8	
0	1,900 (4,700)	24	24	24	24	24	24	24	24	24	24
1,900 (4,700)	2,500 (6,200)	8	16	16	16	16	24	8	8	16	12
2,500 (6,200)	3,900 (8,800)	4	8	8	8	8	16	8	8	4	4
3,900 (8,800)	4,900 (12,400)	.4	0.8	.4	.2	.4	16	.8	.8	.4	.4
4,900 (12,400)	5,900 (15,500)	.2	0.4	.2	.1	.1	.2	.8	.8	.2	.2
5,900 (15,500)	7,000 (160,000)	.05	0.1	.05	.02	.02	.05	.05	.1	.05	.05
7,000	100,000	.05	0.1	.05	.02	.02	.05	.05	.1	.05	.05

[A] Upper numbers denote Toutle River discharge and lower numbers (in parentheses) denote Cowlitz River Discharge

5.1.1.4 Cross-section averaging

Initial results from model runs with default computational options showed abrupt changes in cross-section invert elevation approximating an oscillation. These inconsistent abrupt changes were thought to be the result of computational anomalies. As a result, the number of upstream and downstream cross sections that were used for averaging hydraulic properties was increased from the default value of one cross section to two cross sections. This change had the effect of smoothing out the depositional profile, while maintaining general accuracy.

5.1.1.5 Inflowing sediment load for calibration model

The only significant source of sediment load to the lower Cowlitz is generated from the Toutle River basin. For calibration purposes, the yearly estimate of sediment load from the Toutle River Basin is estimated in a Sediment Budget prepared in 2010. Details of these yearly

estimates can be found in the 2010 SBR, finalized in May 2010. The sediment budget estimates were used in calibration due to the coincident time periods.

Daily estimates of sediment load were derived from a combination of yearly estimates of the sediment load and a robust data set from a USGS gage along the Toutle River at Tower Road (USGS 14242580). Total yearly sediment load was transformed to daily load using the measured daily distribution relationships at the Tower Road gage. Once a daily load was created, it was split into appropriate gradations based on the findings in the 2010 SBR. Yearly and daily estimates of the sediment load at the mouth of the Toutle River are presented in Section 4.3. Fine material, silts and clays, are present in about 42% of the upstream sediment load. This material, while making up a significant percentage of the total sediment load, is easily transported through the system. All sands combine to make up approximately 56% of the total sediment load. Gravel and coarser material make up the least amount of sediment inflow at about 2% of the total load.

5.1.2 Calibration

5.1.2.1 Approach

Because the sediment transport hydraulic model was derived from a calibrated hydraulic model, no further investigation into the results from the fixed-bed analysis was necessary. It was necessary, however, to evaluate mobile-bed parameterization so that appropriate sediment transport characteristics could be achieved. The approach for calibrating the results from the mobile-bed model involved comparing the computed channel aggradation or degradation within the limits of the model over a time period for which relevant survey data had been acquired. Calibration parameterization involved adjustment of the sediment transport equation. Since bed gradation is based on bed material samples and the incoming sediment load was based on upstream modeling results, neither parameter was used for calibration purposes. Future alternative analysis will necessarily require that incoming load not be used as a calibration parameter and necessitated the addition of calibratable transport equations in HEC-RAS. The following section describes in detail the method and results of the calibration of the mobile-bed model.

For calibration purposes, the mobile-bed model was set to run for a period of time that incorporates periods of cross-section survey. Table 5.3 summarizes the surveys collected along the Lower Cowlitz River that were used for calibrating/verifying the results of the mobile-bed model.

Table 5.3 Summary of Survey Data Used for Calibration purposes on the Lower Cowlitz River

Date	Type
August 2003	Hydrosurvey (RM 0.01 to RM 19.52)
April 2006	Hydrosurvey (RM 0.01 to RM 10.3)
December 2006	Hydrosurvey (RM 0.01 to RM 19.52)
June 2008	Hydrosurvey (RM 0.01 to RM 19.52)

These data, although discrete, represent periods of time in which storm events were known to have caused significant movement of bed material. While limitations in the computation algorithm of the mobile-bed model do not necessarily allow prediction of sediment load caused by a single event, the results from the mobile-bed model do allow representation of long-term trends in the sediment load, deposition, and aggradation of the Lower Cowlitz channel. It is the long-term trends of the mobile-bed model that were calibrated such that the long-term prediction out to 2035 could be as accurately represented as possible.

5.1.2.2 Survey/validation data

The survey data for the time periods summarized in Table 5.3 were brought into a standard fixed-bed HEC-RAS model as separate geometry files for each year surveyed. A fixed water surface elevation was applied to each cross section such that the variation in bed geometry could be captured in HEC-RAS conveyance volume computations. The water volume between each cross section was extracted for each survey year from the hydraulic model. Because the water surface elevation was fixed, defined as a known water surface elevation in HEC-RAS, comparisons between surveys could be made and depositional volumes for each time period could be ascertained. Figure 5.4 shows the measured depositional volume from Aug 2003 to Jun 2008.

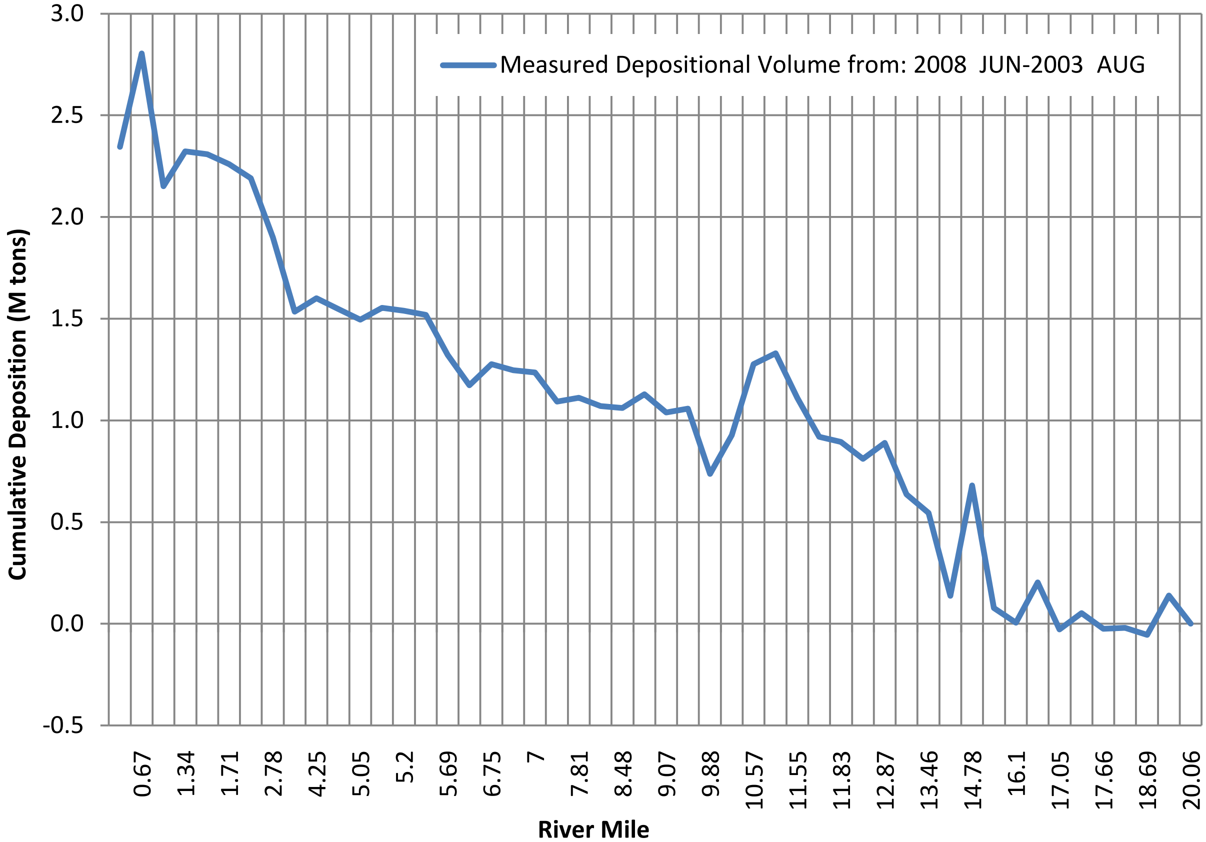

Figure 5.4 Measured Cumulative Deposition from Aug 2003 to Jun 2008

5.1.2.3 Boundary conditions

For the calibration of the mobile-bed model, sediment inflow was determined from an accounting of contributions from all upstream sediment sources. Gage information at Tower Road was used to appropriately distribute the total computed sediment load over the calibration time period. Details regarding the determination of the upstream sediment sources can be found in Chapter 4.0 of this report or in the 2010 SBR. The boundary conditions for the mobile-bed model relied on data from the 2010 SBR to describe a time series of sediment load into the upstream end of the model for calibration (Table 5.4). Since the purpose of calibration of the mobile-bed model was to facilitate long-term prediction of degradation or aggradation trends in the Lower Cowlitz River, the long-term volume data from 2003 to 2008 were used for comparison with results from the mobile-bed model.

Table 5.4 Boundary Conditions Used in Quasi-unsteady Flow for Mobile-bed Computations

Location	Source
Upstream Flow Rate at RM 20.0	Cowlitz River at Castle Rock (USGS 14243000) minus Toutle River at Tower Road (USGS 14242580)
Lateral Inflow at RM 19.52 (Toutle River)	Toutle River at Tower Road (USGS 14242580)
Lateral Inflow at RM 1.71 (Coweeman River)	Basin ratio based on comparisons with nearby USGS gage data
Downstream Water Surface Elevation at RM 0.01	National Oceanic and Atmospheric Administration (NOAA) Gage at Longview (NOAA 9440422)

The hydraulically calibrated fixed-bed model obtained from the 2009 LOP analysis computed a series of steady-state profiles used in the evaluation of the levee performance. Since the LOP model is designed to model only high flows, the calibration coefficients encoded were for peak events. Variation in roughness associated with bed form regime change has been observed and analyzed for the lower reach with a sand bed. This was incorporated into the model as vertical variation in roughness to more accurately describe the hydraulics through the complete flow range as all flows are used in the calibration and long-term mobile-bed model runs. The mobile-bed model required the use of quasi-steady state, which defined the flow rates and the downstream boundary conditions as a time series of steady-state runs through the calibration time period. Flow rate boundary data were obtained along the Cowlitz River at Castle Rock, along the Toutle River at Tower Road, and along the Coweeman River from a 2009 hydrologic study of the Cowlitz River Basin. Downstream starting water surface elevation was obtained from NOAA gage number 9440422 at Longview, WA.

5.1.2.4 Transport function

The Laursen-Copeland transport equation was used in the mobile-bed model of the Lower Cowlitz River. This transport equation is applicable for a wide range of sediment size classes including silts. It is this applicability to a wide gradation range that makes the Laursen-Copeland suitable for the reach of the Lower Cowlitz River included in the mobile-bed model.

Laursen-Copeland's transport equation consists of an excess grain shear type computation to determine the sediment discharge concentration. The formulation of the Laursen-Copeland's transport equation used in HEC-RAS is shown in Equation 5.1 (USACE 2010):

Laursen-Copeland: $$C_m = 0.01\gamma \left(\frac{d_s}{D}\right)^{7/6} \left(\frac{\tau' - \tau_c}{\tau_c}\right) f\left(\frac{u_*}{\omega}\right)$$ **Equation 5.1**

where,

C_m	=	sediment discharge concentration (weight/volume);
γ	=	unit weight of water (weight/volume);
d_s	=	mean particle diameter (L);
D	=	effective depth of flow (L);
τ'	=	bed shear due to grain resistance (pressure);
τ_c	=	critical bed shear stress (pressure); and
$f\left(\frac{u_*}{\omega}\right)$	=	empirical function, where u_* is shear velocity (L/T) and ω is fall velocity (L/T).

The basic form of the Laursen-Copeland transport equation shown in Equation 5.1 includes three key calibration parameters: 1) an overall coefficient (default value of 0.01), 2) a power of the fundament transport engine or excess grain shear computation (default of 1.0), and 3) critical shear stress, τ_c (default value of 0.039). These three parameters were systematically altered from the default values such that the overall depositional trends match what was measured.

5.1.2.5 Calibration results

By running a large number of possible coefficient combinations, a specific sediment transport function was tailored to specifically meet the needs of the measured data. The results of the final calibration is shown in Figure 5.5. Equation 5.2 shows the resulting version of the Laursen-Copeland transport function. The coefficient (0.008), critical shear stress (0.037), and power (1.57) were established from determining results that best fit the surveyed data:

$$C_m = 0.008\gamma\left(\frac{d_s}{D}\right)^{7/6}\left(\frac{\tau' - 0.037}{0.037}\right)^{1.57} f\left(\frac{u_*}{\omega}\right) \qquad \textbf{Equation 5.2}$$

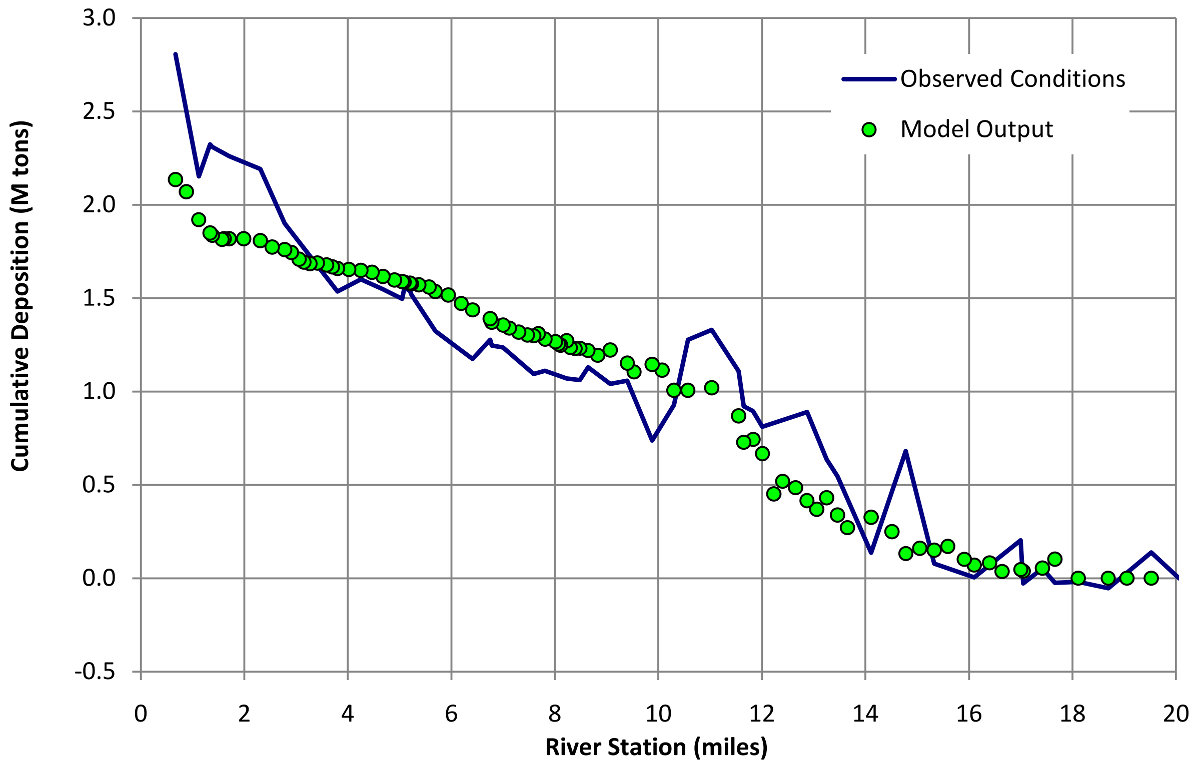

Figure 5.5 Observed and Model Cumulative Deposition

5.1.3 Long-term Forecast Run

5.1.3.1 Approach

From the results of the calibration tests, the Laursen-Copeland sediment transport equation, with modified coefficients, was used in the long-term mobile-bed simulation. Sediment load delivered to the upstream end of the Lower Cowlitz model was estimated through the use of computer simulations of the long-term aggradation and degradation of the SRS and estimation of sediment loads from the South Fork of the Toutle, Green River, and from bank erosion in the Lower Toutle River. Both 1-D and 2-D models were developed to model the sediment plain behind the SRS; however, only the sediment load estimates that included results of the 2-D model were used for the final Lower Cowlitz River modeling. Since the complete modeling scheme used is fundamentally a deterministic alternative analysis and plan selection, only a single final solution can be developed. The 2-D results are felt to be a superior representation of the system as they more accurately capture the complex hydraulics in the braided system upstream of the SRS.

While sufficient data were available to support modeling efforts for the period from 1999 to 2007, forecasting sediment loads out to 2035 required a method to predict future sediment loads. To predict future sediment loads, data from 1999 to 2007 were used in series as a

surrogate for measured data. The upstream SRS models were run for a specific sequence of surrogate years. The selected sequence used to forecast sediment load into the Lower Cowlitz River is discussed in Section 2.5. Results from the upstream model for these forecasting years were handed down to the Lower Cowlitz model.

5.1.3.2 Inflowing sediment load for long-term model

Results from long-term 2-D mobile-bed modeling of the sediment plain behind the SRS were used in conjunction with downstream sediment sources as input into the long-term Lower Cowlitz 1-D mobile-bed model. The 2-D model duration is coincident with the long-term 1-D model. The 1-D mobile-bed model was set to read in time series sediment load from a Data Source Selection (DSS) data file. The data file was created to include daily estimates of the sediment load from the Toutle River Basin for various grain sizes as well as a total sediment inflow volume. Section 4.3 presented the makeup of the sediment inflow from the Toutle River for the long-term model.

5.1.3.3 Inflowing sediment gradation

The total 203 M Tons was distributed by grain size based on a combination of bed and suspended sediment sampling throughout the Toutle Basin. Chapter 4.0 discussed the gradation distribution used for the Toutle River sediment load in more detail.

The largest quantity from a single gradation class consists of fine material, silts that range from 0.032 mm to 0.625 mm. Fine, medium, and coarse sands together make up the overall largest amount of sediment load from the Toutle. Gravel load occupies only a small amount of the total load coming into the Cowlitz River. Figure 5.6 shows the amount by percentage of silt, sand, and gravel coming into the Cowlitz River from Toutle River sources.

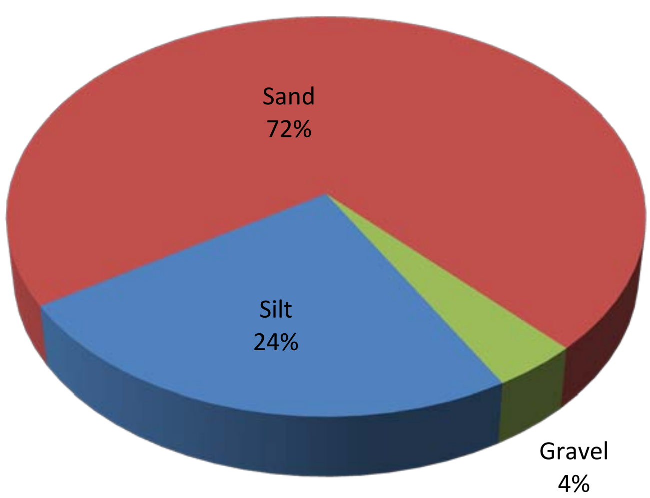

Figure 5.6 Characteristics of Incoming Sediment Load (2-D Model)

At 72%, sand occupies the largest amount of load coming into the Lower Cowlitz followed by 24% silt. Of the total Toutle River sediment load, only 4% is estimated to be gravel. Characterization of the sediment load from the Toutle River is useful when comparing the results from the mobile-bed model.

5.1.3.4 Long-term forecast results

The fundamental purpose of developing the Lower Cowlitz mobile-bed model was to quantify and describe the sediment load that deposits adjacent to the Cowlitz River levees. Figure 5.7 summarizes the deposition of sediment load over the entire 20-mile reach modeled out to 2035. The total load deposited at the end of this time period is approximately 38 M Tons. Significant deposition occurs following the large hydrologic events that occur in 2015 and 2030. Significant deposition is also observed in 2021, which corresponds to the large 1999 event.

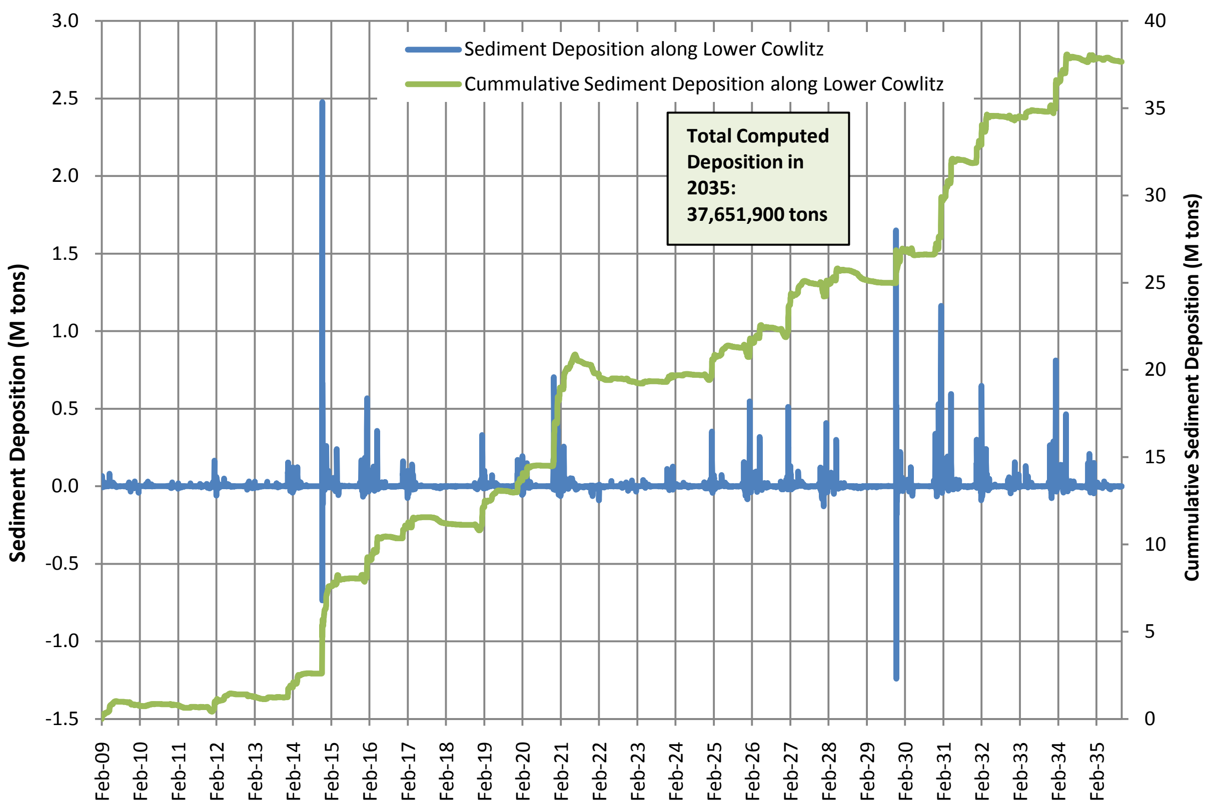

Figure 5.7 Deposition Mass from Long-term Simulations over the Entire Lower Cowlitz Reach

In addition to the overall reach summation, the total deposition computed by the mobile-bed Cowlitz model was compiled into five separate reaches from 2010 to 2035. Figure 5.8 is a plot of the deposition computed for each reach normalized according to the corresponding reach length. The selected reaches are denoted by the bounding cross sections and the abutting levees. The reach evaluation begins in 2010 to avoid any anomalies caused by the model

starting conditions. The mass indicated at 2035 represent the total normalized mass deposited during the period from 2010 to 2035. Figure 5.8 shows a greater amount of deposition in the upstream reaches, from RM 20.01 down to RM 9.53, than in the reaches below RM 9.53. From the data presented in Figure 5.8, for the 25-year period from 2010 to 2035, the downstream reach averaged about 1.2 M Tons per mile, while the upstream reaches were approximately 2.5 M Tons per mile.

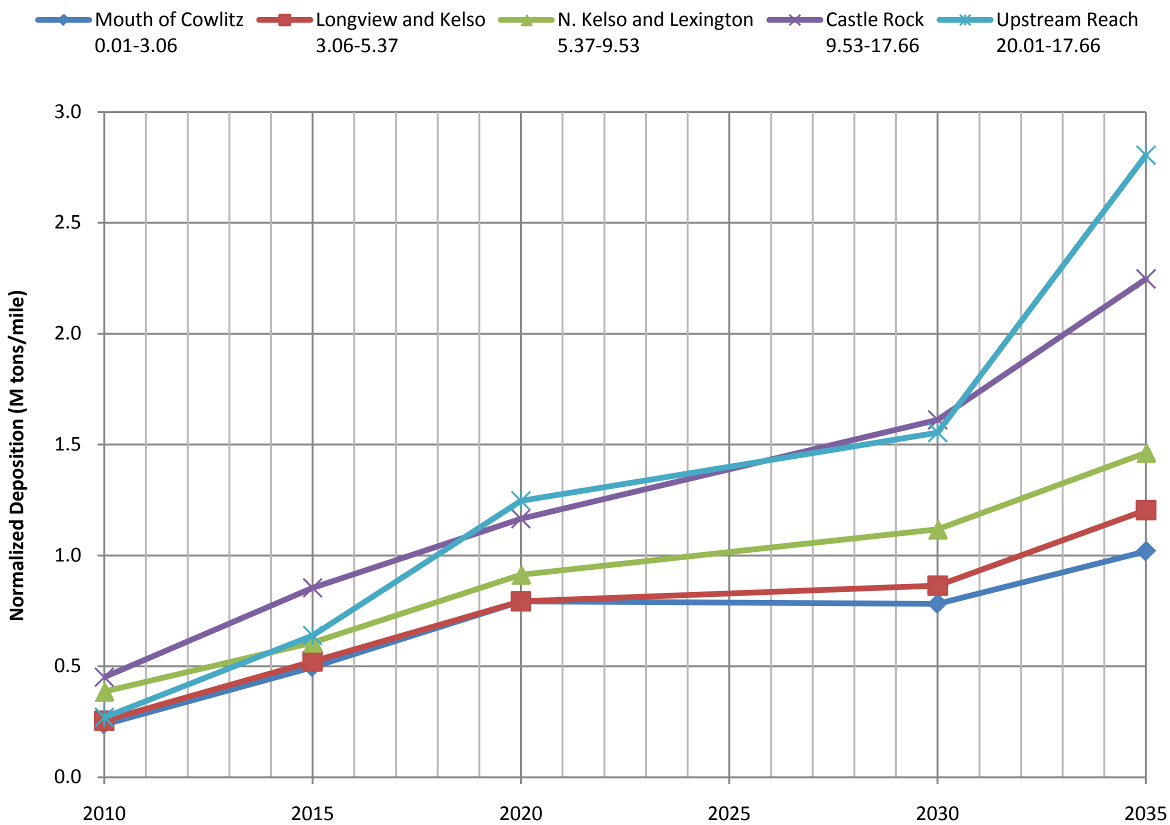

Figure 5.8 Total Deposition per Mile by Reach from 2010 to 2035

The total mass deposited from the period 2010 to 2035 can be broken down into individual size fraction to give a sense of what material makes up the majority of the depositional mass. Figure 5.9 shows the breakdown of what size fraction makes up the depositional mass.

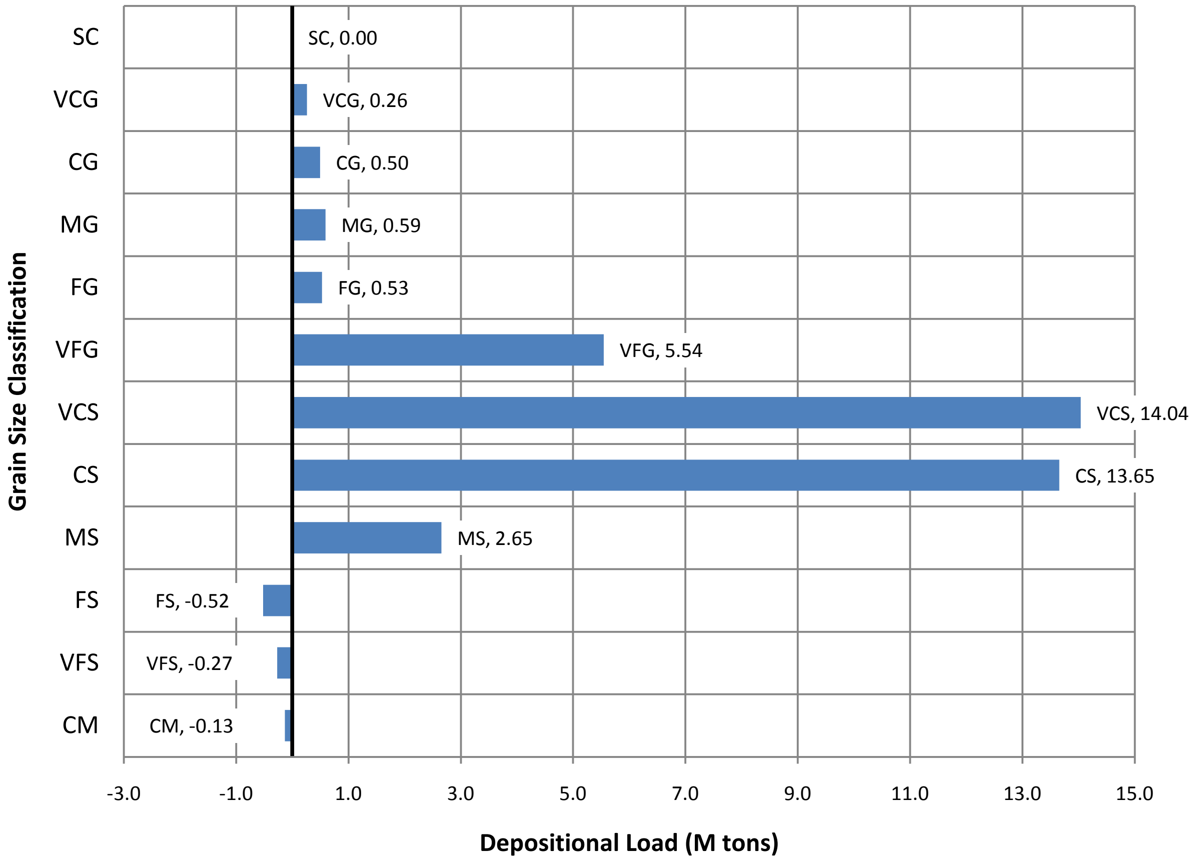

Figure 5.9 Depositional Volume by Grain Class for the Entire Reach from 2010 to 2035

From the results of the mobile-bed model of the Lower Cowlitz, coarse sand and very coarse sand are responsible for nearly 80% of the deposited mass. Roughly 20% of the deposited mass consists of gravel despite the fact that only 4% of the incoming load is made up of gravel. Finer sands and silts, while present in large quantities in the incoming sediment load, are generally washed through the Cowlitz River. Figure 5.10 summarizes the basic characteristics of the total volume deposited for the entire modeled reach out to 2035.

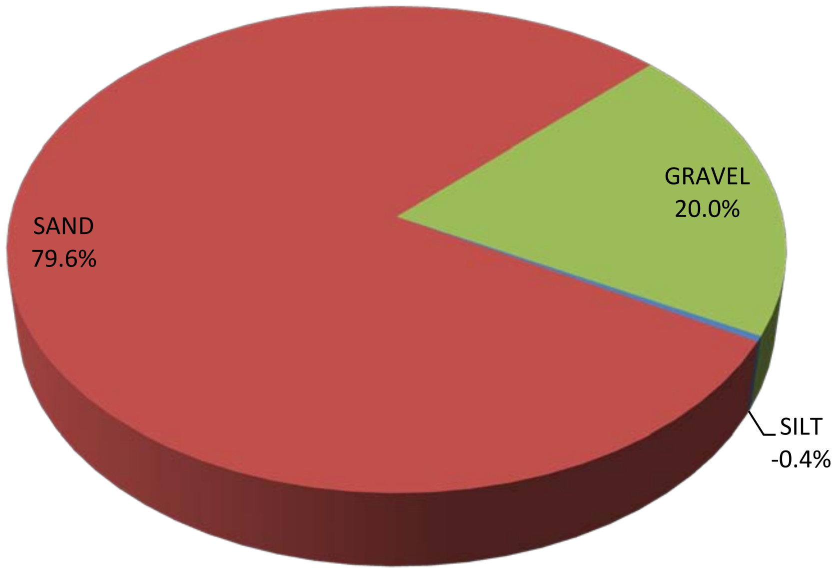

Figure 5.10 Characteristic of Sediment Deposition for the Entire Reach out to 2035

5.1.4 Development of Input to Lower Cowlitz 2-D Modeling

To support downstream 2-D modeling at the mouth of the Cowlitz River, sediment output from the 1-D model was extracted at RM 4.68, which corresponds to the upstream limits of the 2-D model. Daily total sediment load and daily load per grain class were used as upstream boundary conditions for the 2-D model. Figure 5.11 shows the daily load and the cumulative load at RM 4.68 and Figure 5.12 shows the total sediment load by grain class at RM 4.68.

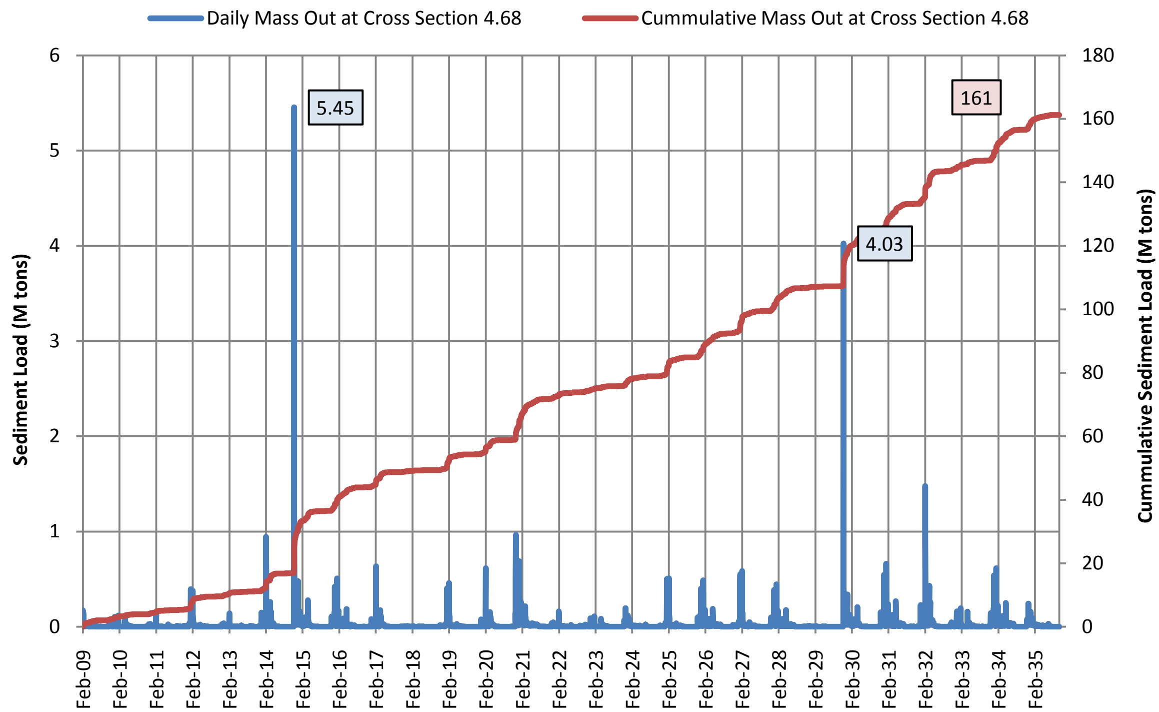

Figure 5.11 Daily Sediment Load from the 1-D Model at RM 4.68 (data used in 2-D model at the mouth of the Cowlitz River)

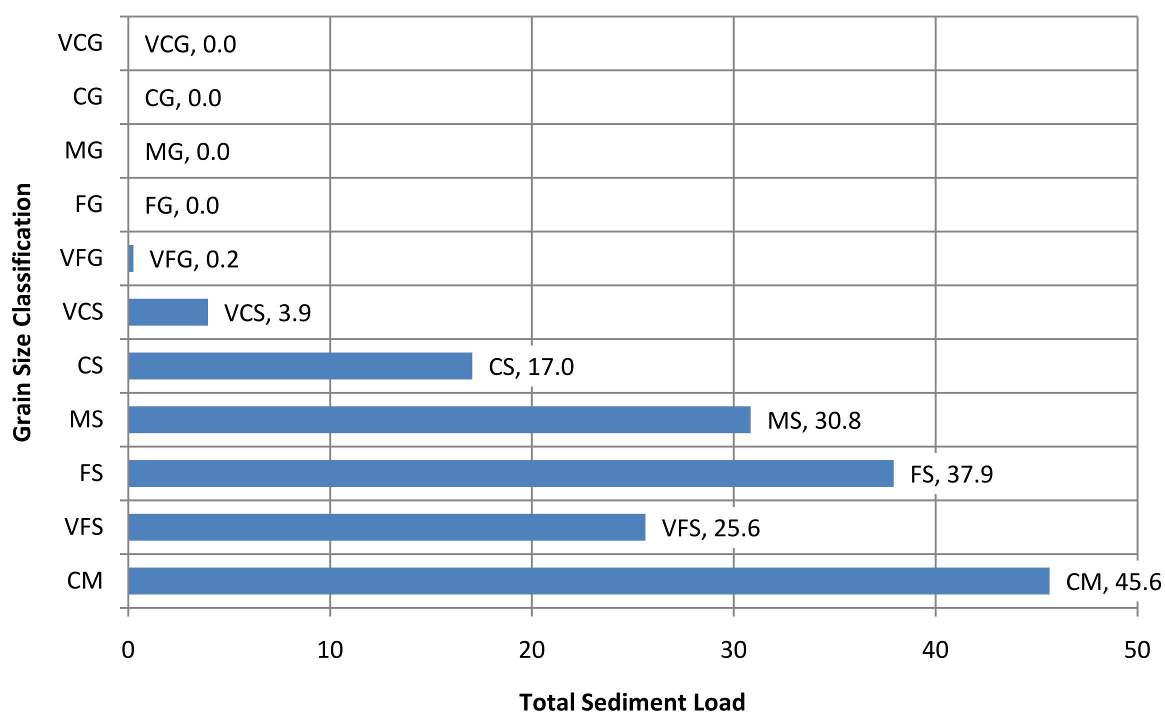

Figure 5.12 Sediment Load by Grain Class at RM 4.68 (data used in 2-D model at the mouth of the Cowlitz River)

In addition to a total daily sediment load, the daily sediment load by grain class was extracted from the mobile-bed model at RM 4.68 and used to support the 2-D modeling at the mouth of the Cowlitz River.

Comparison of the sediment load characteristics passing RM 4.68 in Figure 5.12 and the depositional load over the entire reach shown in Figure 5.9 indicates that the material responsible for channel deposition consists of coarse sand and very coarse sand. Figure 5.12 shows that fine sands to silts are generally carried by the flow through the downstream end of the Cowlitz River eventually reaching the Columbia River.

5.2 Lower Cowlitz River 2-D MIKE 21C Model

A fully coupled 2-D hydrodynamic model was created of the lower 4.5 miles of the Cowlitz River from just downstream of the Allen Street Bridge to the Cowlitz - Columbia River confluence (see Figure 5.13). The model also includes Carol's Channel and the Columbia River from upstream of Carol's Channel to about a mile downstream of the Cowlitz - Columbia River confluence. Sediment outflow from the Upper Cowlitz River 1-D sediment transport model was added to the 2-D model and a period of representative years from Aug 2004 to Aug 2007 were studied to better understand sedimentation trends in this area with respect to this FEDS study.

Figure 5.13 Lower Cowlitz River Model Location

The modeling results indicate that the Lower Cowlitz study reach is generally depositional in character. After the 3-year study period, the model predicted about 4.5 M Tons of material deposits in the Lower Cowlitz model reach.

5.2.1 Modeling Approach

The hydrodynamic module simulates water surface level and lateral and longitudinal velocity variations in response to a variety of forcing functions, including upstream Cowlitz River flow volume, tributary Coweeman River inflow, downstream Columbia River water surface elevation (which is a function of tide and incoming Columbia River flow in this system), bed shear stress, wind shear, barometric pressure, Coriolis acceleration, momentum dispersion, sources and sinks, evaporation, flooding and drying, and wave radiation stresses. Since the goal of this study is to evaluate the progressive change in bed geometry of the Cowlitz River, and to ultimately compare the FEDS case with alternative management concepts (including dike fields and varied sediment inflow from upstream dependent on changes to the SRS and the study reach above the SRS) wind shear, barometric pressure variation, evaporation, and wave radiation stresses were omitted.

5.2.2 Model Development

5.2.2.1 Model grid

MIKE 21C operates exclusively in SI units and is based on a curvilinear grid. A curvilinear grid is similar to a structured grid in that each cell has four sides; however, the cells can be non-orthogonal and bend to better represent the sinuosity of natural river systems. The grid for the Lower Cowlitz River includes the lower 4.5 miles of the Cowlitz River and about 6 miles of the Columbia River (just over a mile downstream and about 5 miles upstream from the Cowlitz including Carol's Channel). The 45,000-cell grid (302 cells in the Cowlitz River direction x 149 cells in the Columbia River direction) is shown in Figure 5.14. A small section of the model mesh is shown at an exaggerated scale (inset) to illustrate the cell density and the orientation of the 2-D grid layout.

The resolution of the grid cells in the main flow channel of the Cowlitz River varies but is approximately 20 m in the j or flow direction by 10 m in the k or cross-flow direction (66 ft x 33 ft). This level of detail will allow future incorporation of sediment transport enhancing structures (i.e., dikes) into the model and still allows for reasonable run times. The FEDS model requires about 80 hours of computer time to run the 3-year hydraulic and sediment inflow hydrograph with a 4-second hydraulic time step (the sediment transport equations are updated every thirty hydraulic time steps or every 2 minutes).

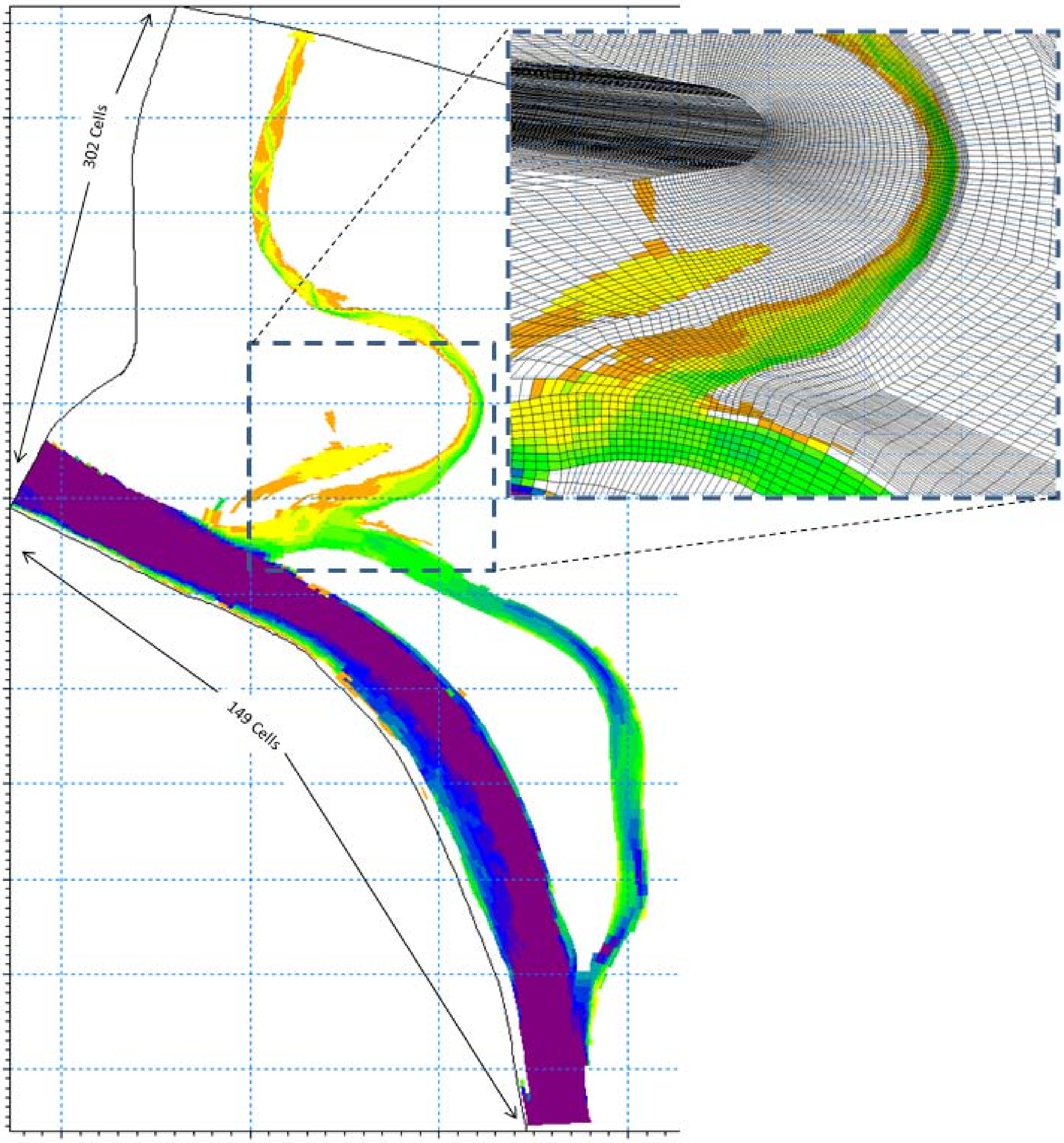

Figure 5.14 Lower Cowlitz Model Mesh

5.2.2.2 Bathymetry

The model bathymetry (representing the river bed or physical channel geometry) was developed using hydrographic data collected by the USACE from Feb 2008, May 2008, and 2009 cross sections which were interpolated into a surface. The overbank areas were generated by using 2010 LiDAR data. The horizontal datum of the survey data is NAD83 Washington State Plane (South) and the vertical datum is NAVD88. The survey data were translated into Universal

Transverse Mercator (UTM) coordinates (Zone 10N) and the vertical datum was changed to meters for use in the Lower Cowlitz MIKE 21C model, which requires all input to be in SI units.

By emphasizing topographic detail in the direction of Cowlitz River flow, a smooth conveyance channel was created. High land elevations values of 20 m were assigned to cell areas outside the channel to reduce the number of potential wet cells within the grid and accelerate computation times. Figure 5.15 shows the Lower Cowlitz River model baseline bathymetry (all elevations are in meters).

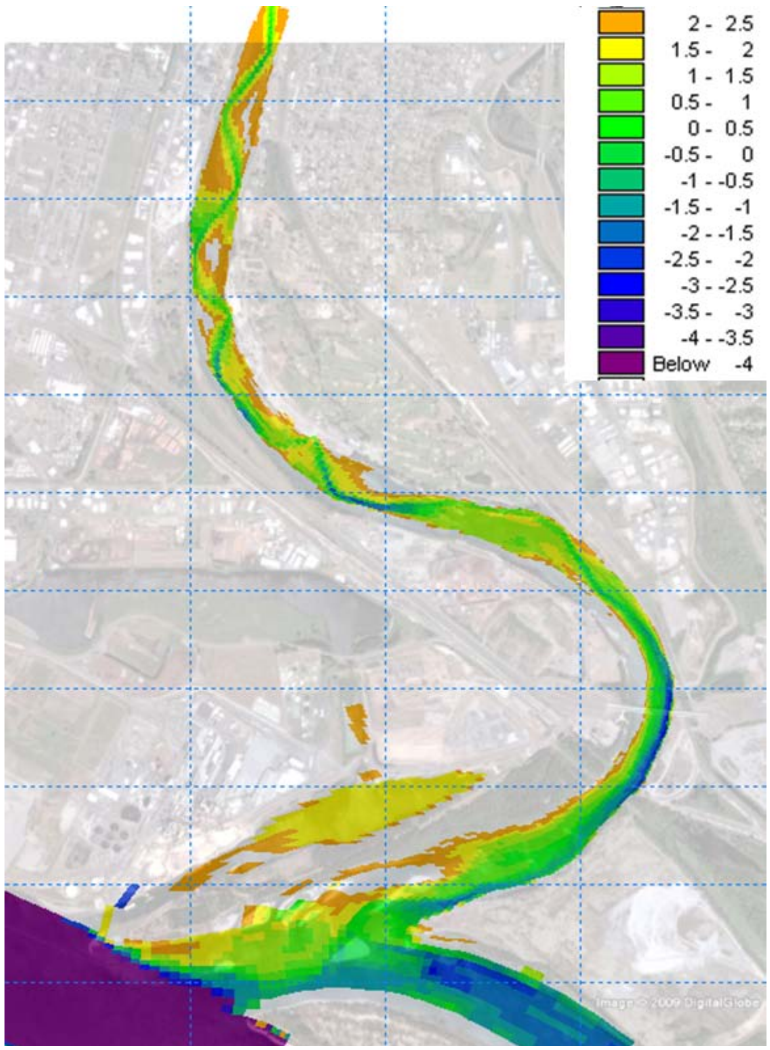

Figure 5.15 Lower Cowlitz Baseline Bathymetry (color-coded elevations are in meters)

5.2.2.3 Hydrodynamic simulation period

Hydraulic data for the Cowlitz (flow), Coweeman (flow), Columbia (upstream inflow and downstream stage) are all necessary as inputs for the 2-D flow model. An overlapping period of record with hourly Columbia River flow and downstream water surface elevation (hourly data are necessary to account for tidal influences within the Columbia River), and mean daily Cowlitz

and Coweeman River flow values is required to satisfy the model boundary conditions. The selected modeling period was between Aug 2004 and Aug 2006 as this period has a low-flow year, a medium-flow year, and a year with a high peak flow as well as coincident Columbia stage and discharge, and Coweeman River and Cowlitz River discharge. Figure 5.16 shows the inflow hydrograph for the Cowlitz River for the modeling period. Cowlitz sediment inflow values (in cubic meters per second for six size fractions ranging from 0.04 to 1.41 mm) was handed off from the Upper Cowlitz 1-D modeling effort as another input parameter for the 2-D model. Since model runs for the 3-year period take about 80 hours of computer time to process, it was decided that understanding the river system's response to three typical but characteristically different years would be useful in evaluating the effect of various upstream and local sediment management strategies in lieu of forcing an unreasonably long model run to include the full 28 future years.

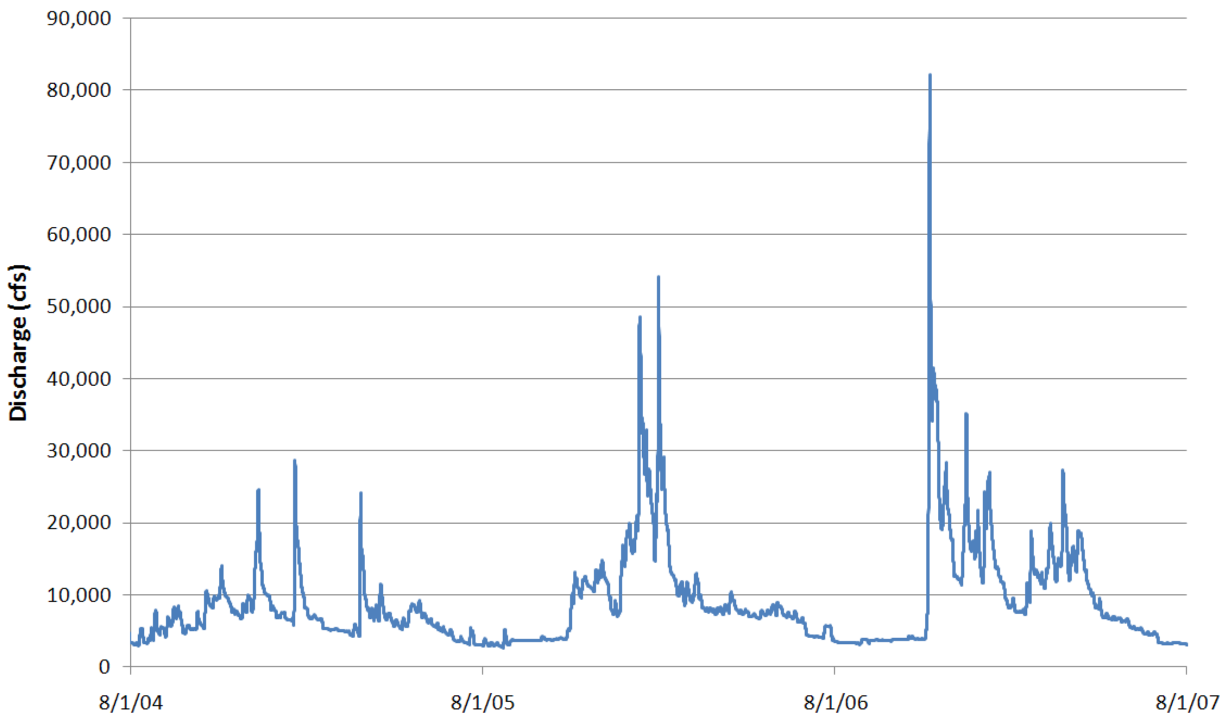

Figure 5.16 Cowlitz River Inflow Aug 2004 to Aug 2007

The ability of the model to generate stable solutions is related to the hydraulic time step length and to grid cell size. High cell resolution (smaller cells) and high-flow velocities require the use of smaller time steps. The Lower Cowlitz River model was found to be stable with a hydraulic time step on the order of 4 seconds. For a 4-second time step the Courant Number (V_C) is less than 0.40 when velocities (u) are less than 2 m/second, and cell size (Δx) is about 20 m in the flow direction. If the Courant Number is greater than 1, a smaller time step should be chosen:

Courant Number: $$V_C = \frac{u \cdot \Delta t}{\Delta x}$$ **Equation 5.3**

The sediment time step was set at 2 minutes so that every 120 hydraulic time steps lead to one sediment transport update and bed recalculation.

Sediment transport functions are selected within MIKE 21C and the transport efficiency can be adjusted to better match specific model conditions. In this case, the model sediment transport efficiency was adjusted to best fit the sediment concentration represented by the inflowing sediment curve. Figure 5.17 shows the modeled sediment concentration within the upstream portion of the study reach for the Laursen-Copeland function, vanRijn, and vanRijn multiplied by 1.9. The vanRijn x 1.9 computed sediment transportation function best matches the inflowing sediment rating curve concentrations below 250 cms (70% of flows between 2002 and 2007 were under 250 cms).

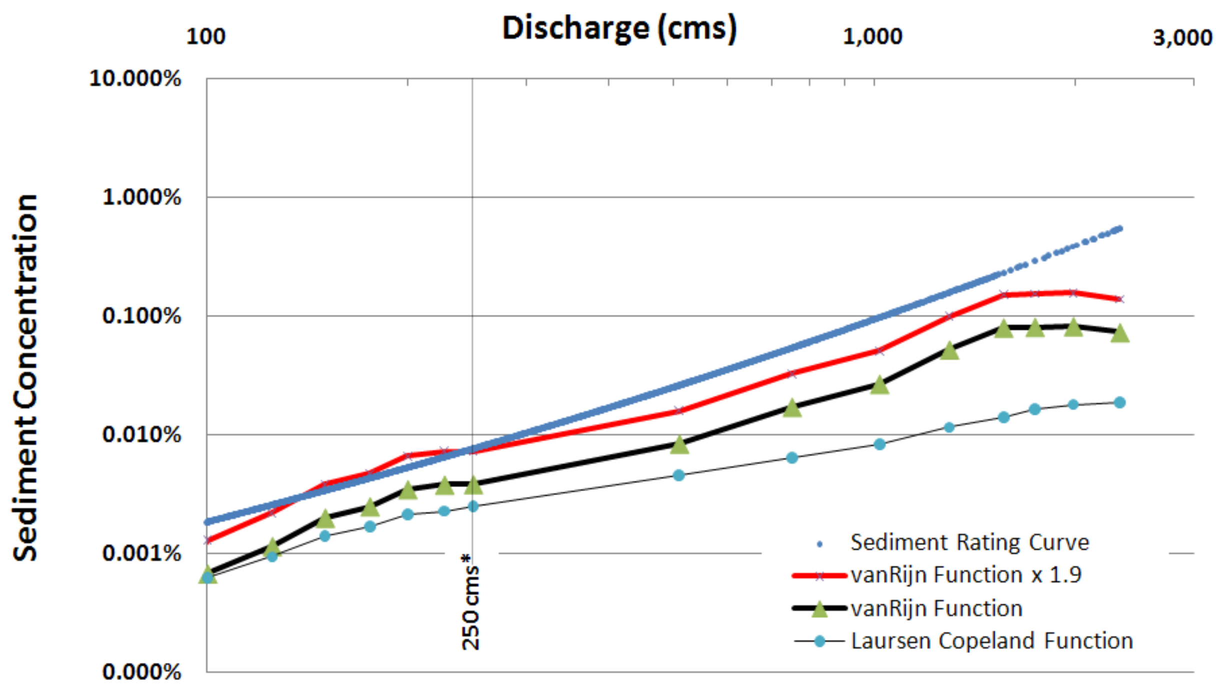

Figure 5.17 Sediment Transport Function Comparison

5.2.2.4 Model boundary definitions

At each model boundary, either a water surface elevation or a flow is specified. In most cases, models will include at least one boundary where water surface elevation is defined and one boundary where flow is given. Additional boundaries can specify water level or flow at other parts of the model.

This model has four model boundaries: 1) the downstream starting water surface elevation in the model is defined on the Columbia River about a mile downstream from the Cowlitz confluence, 2) incoming flow from the Columbia River is input approximately 5 miles upstream from the Cowlitz confluence, 3) Cowlitz inflow and incoming sediment is defined at a boundary

4.5 miles upstream along the Cowlitz River, and 4) Coweeman River inflow is entered upstream from the Highway 432 Bridge. Cowlitz inflow for the period of interest is shown in Figure 5.16. The hourly Columbia River inflow boundary condition is shown for each of the modeled years in Figure 5.18, Figure 5.19, and Figure 5.20. The downstream water surface elevation at the Columbia River boundary is shown in Figure 5.21, Figure 5.22, and Figure 5.23 for the study period. Coweeman River inflow can be seen in Figure 5.24.

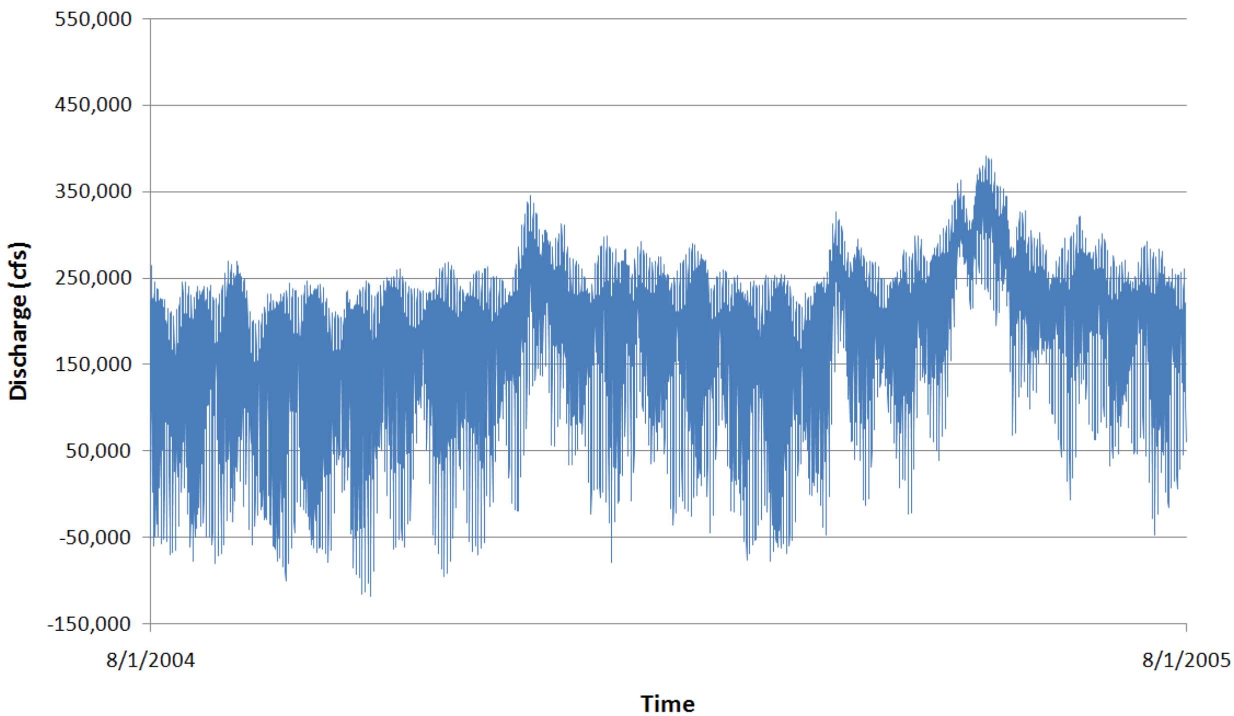

Figure 5.18 Columbia River Inflow, Aug 2004 to Aug 2005

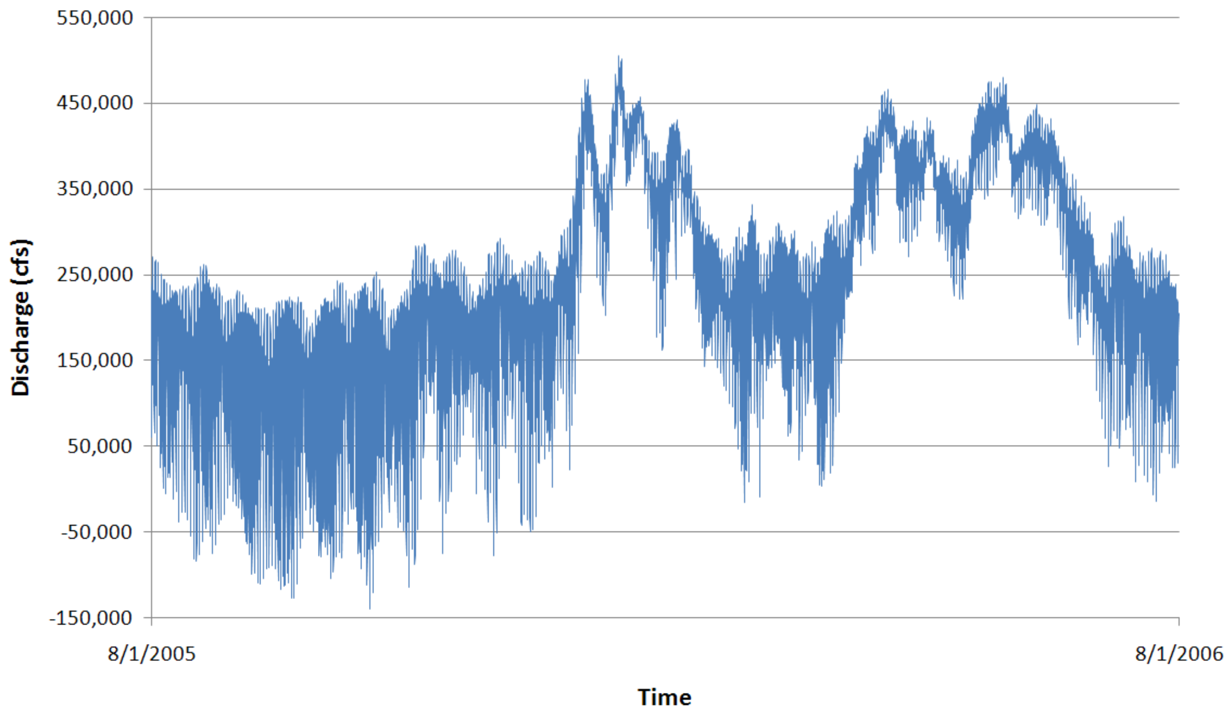

Figure 5.19 Columbia River Inflow, Aug 2005 to Aug 2006

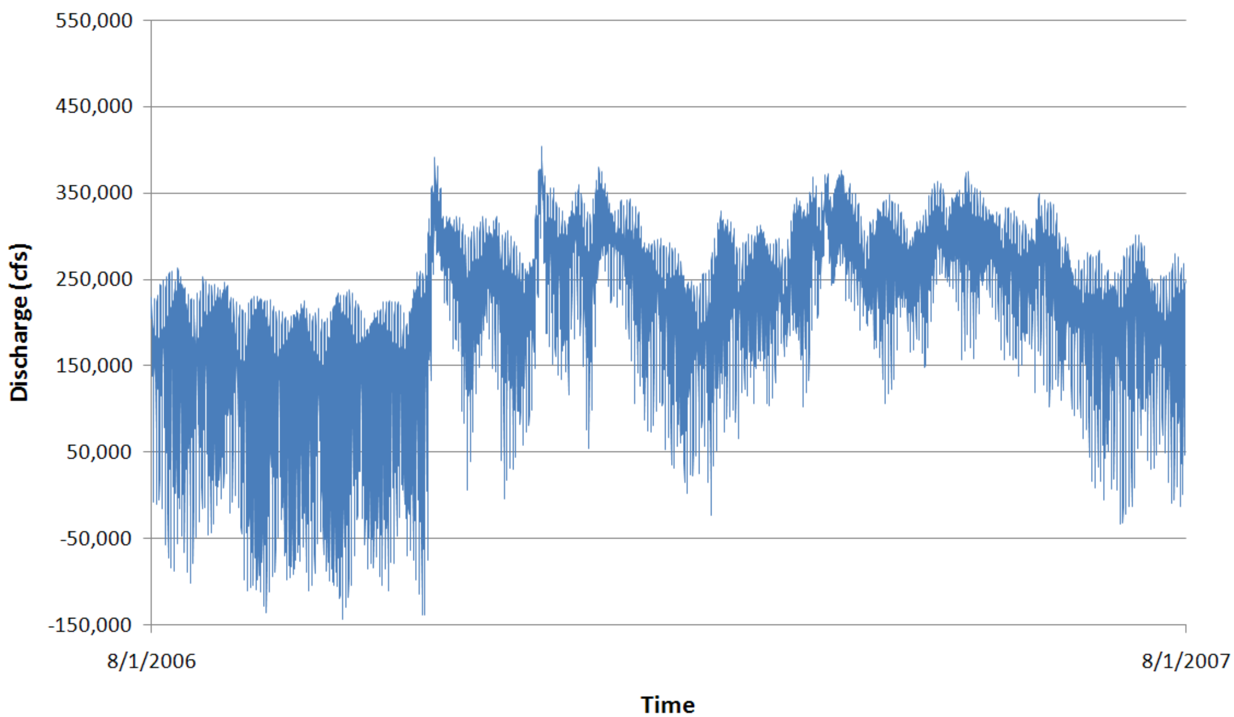

Figure 5.20 Columbia River Inflow, Aug 2006 to Aug 2007

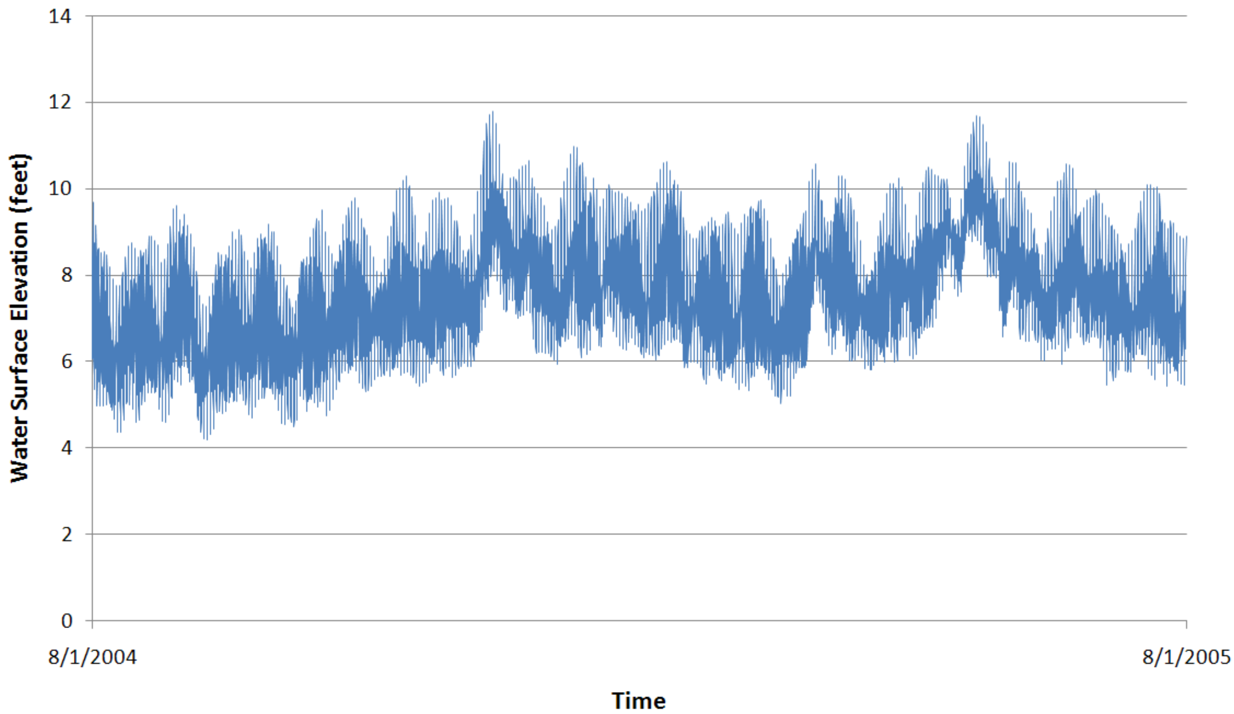

Figure 5.21 Columbia River Downstream Model Water Surface Elevation, Aug 2004 to Aug 2005

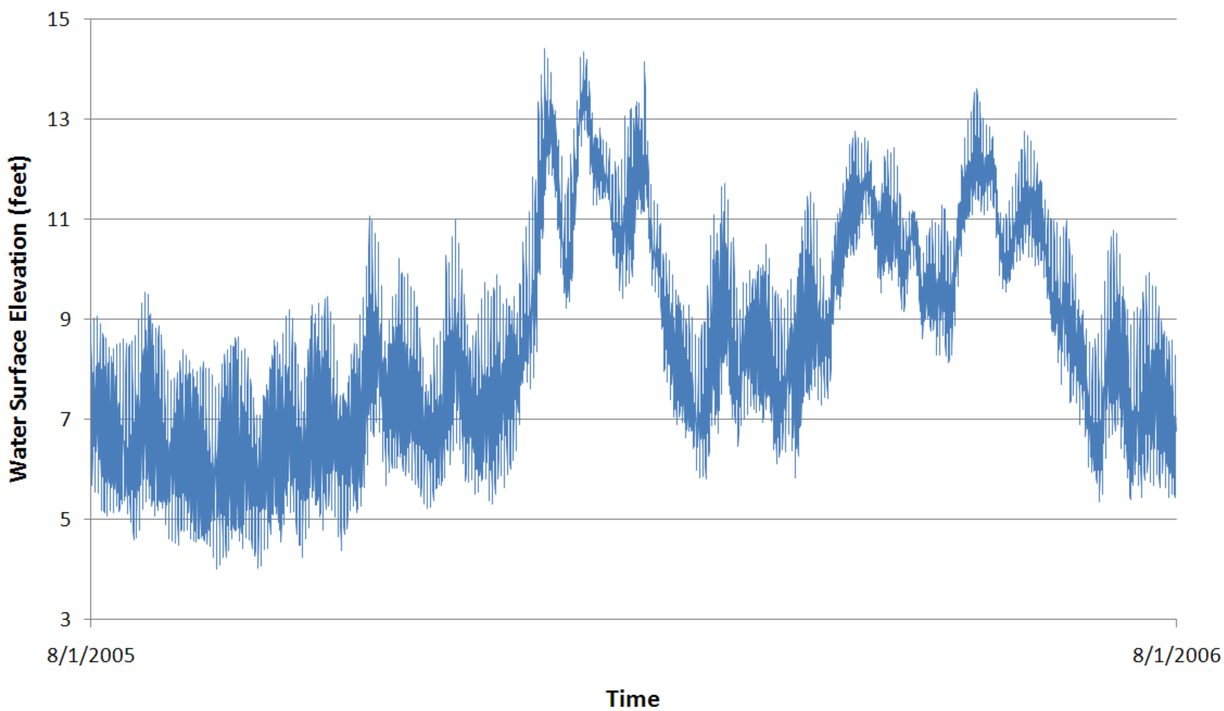

Figure 5.22 Columbia River Downstream Model Water Surface Elevation, Aug 2005 to Aug 2006

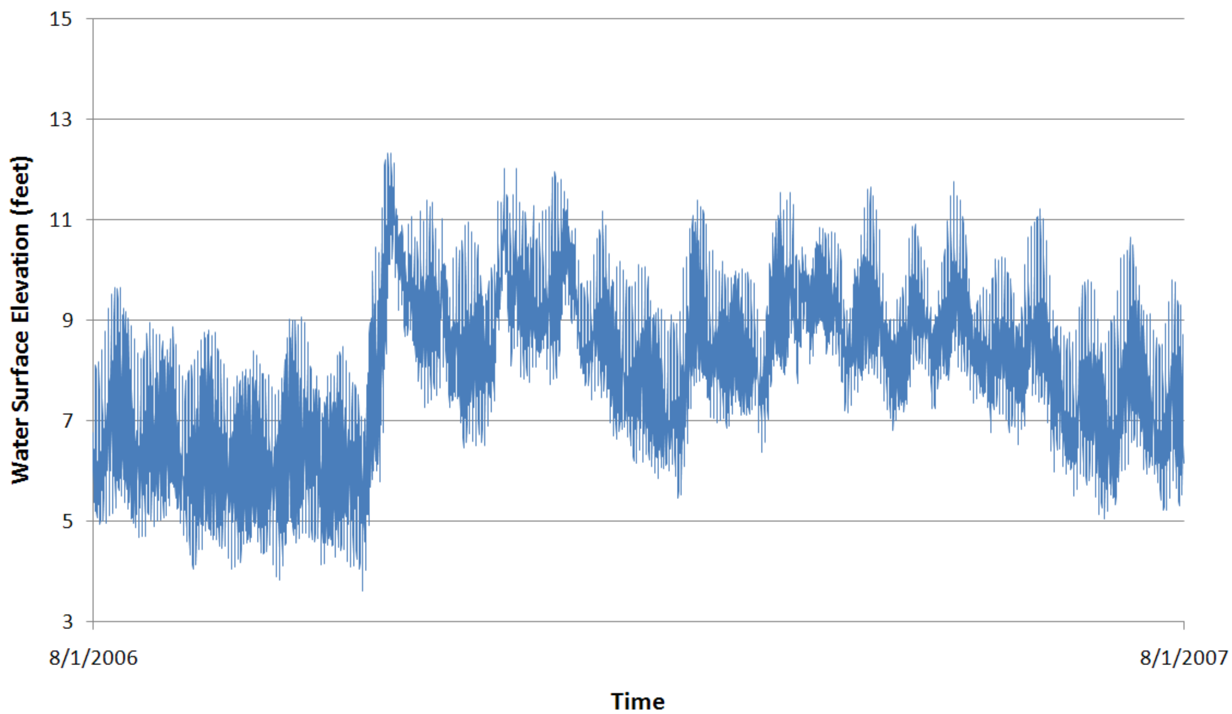

Figure 5.23 Columbia River Downstream Model Water Surface Elevation, Aug 2006 to Aug 2007

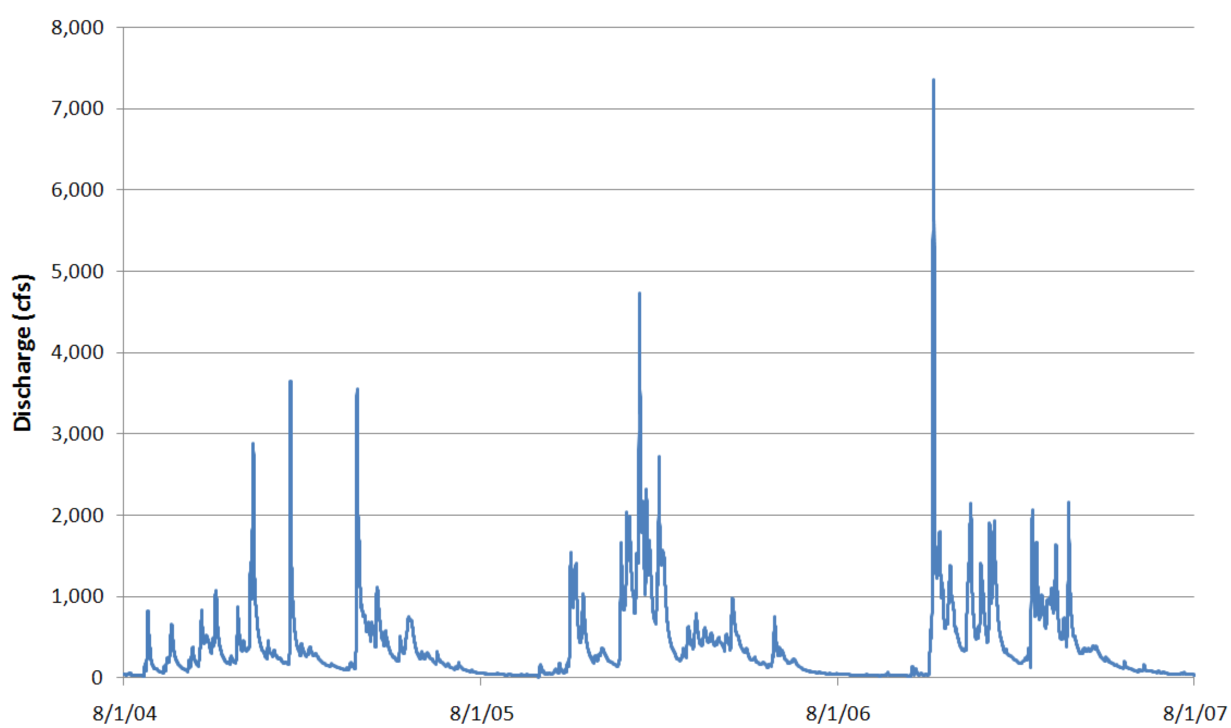

Figure 5.24 Coweeman River Inflow, Aug 2004 to Aug 2007

5.2.2.5 Sediment inflow

Figure 5.25 shows the total sediment inflow curve for the study period. The inset area illustrates the relative amounts of sediment by size class for the period between 12/25/2005 to 2/15/2006. CM has the highest concentration and VCS the lowest (this trend is consistent throughout the time period, fines have the highest concentration and the very coarse sand class has the lowest concentration).

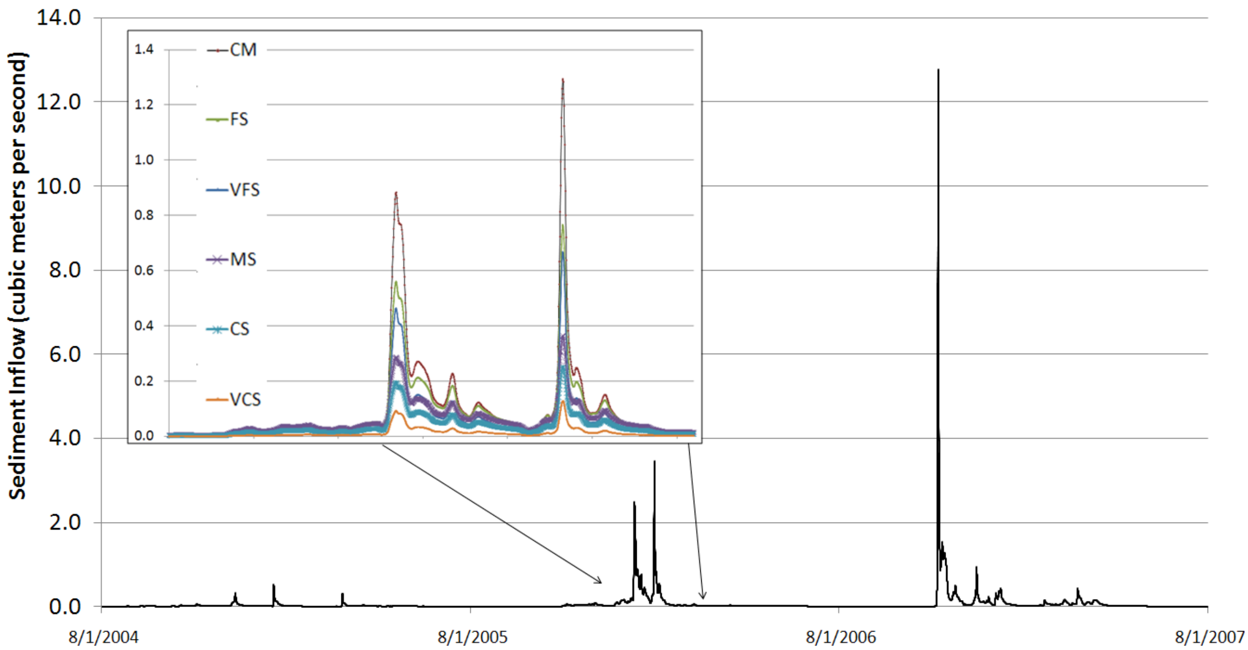

Figure 5.25 Cowlitz River Sediment Inflow, Aug 2004 to Aug 2007 (inset by size fraction)

5.2.2.6 Bed gradation

The 2-D model allows for defining the bed material gradation throughout the study area. For this model, several USACE sediment studies were reviewed including the *Cowlitz River Interim Dredging Design Documentation Report* (USACE 2007b) and *Gradation Data for Recent Deposits Cowlitz RM 0-20* (USACE 1992). An average of representative sediment gradations in the area of RMs 2.5 to 3.5 were used to describe the study reach bed material (see Figure 5.26).

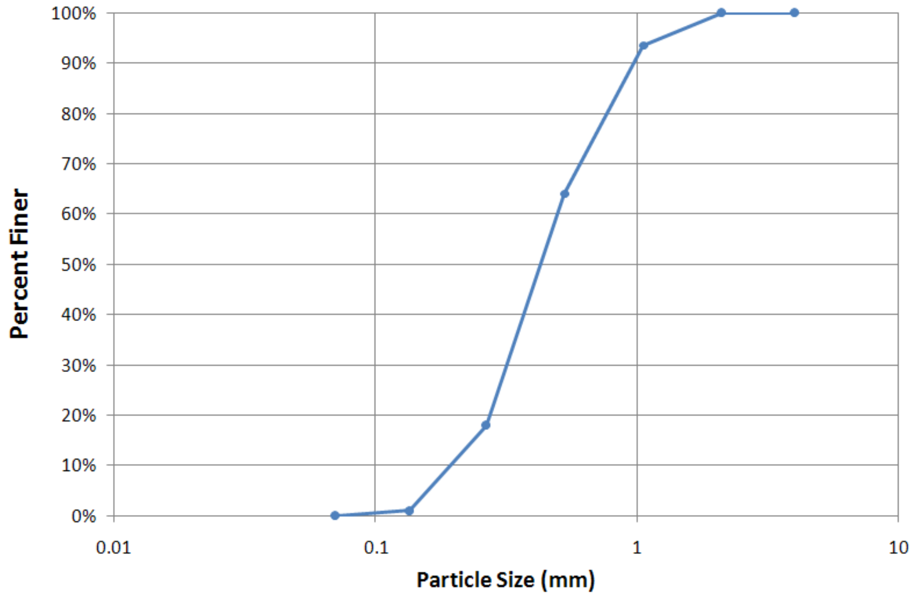

Figure 5.26 Lower Cowlitz River Model Bed Material Gradation

5.2.2.7 Model verification – Gerhardt Gardens Park

To validate the model performance with the bathymetry and boundary conditions described in the previous sections, model output water surface elevation was compared to observed water surface elevations at the Gerhart Gardens gage. Since MIKE 21C output is cell-wise, an average water surface for ten cells in the middle of the river at this section was used in the comparison. Figure 5.27 shows the computed model water surface as compared to gage observations for the period of flow and boundary conditions between 12/2/2008 and 1/12/2009. The verification period was selected as a portion of the coincident boundary condition data availability with a representative period of normal flow and the highest peak water surface elevation (the verification period is highlighted with a red line in Figure 5.28). Most of the output is coincident with observed water surface in this area through the normal flow period, and the model mimics the trend of higher water surface through the peak event.

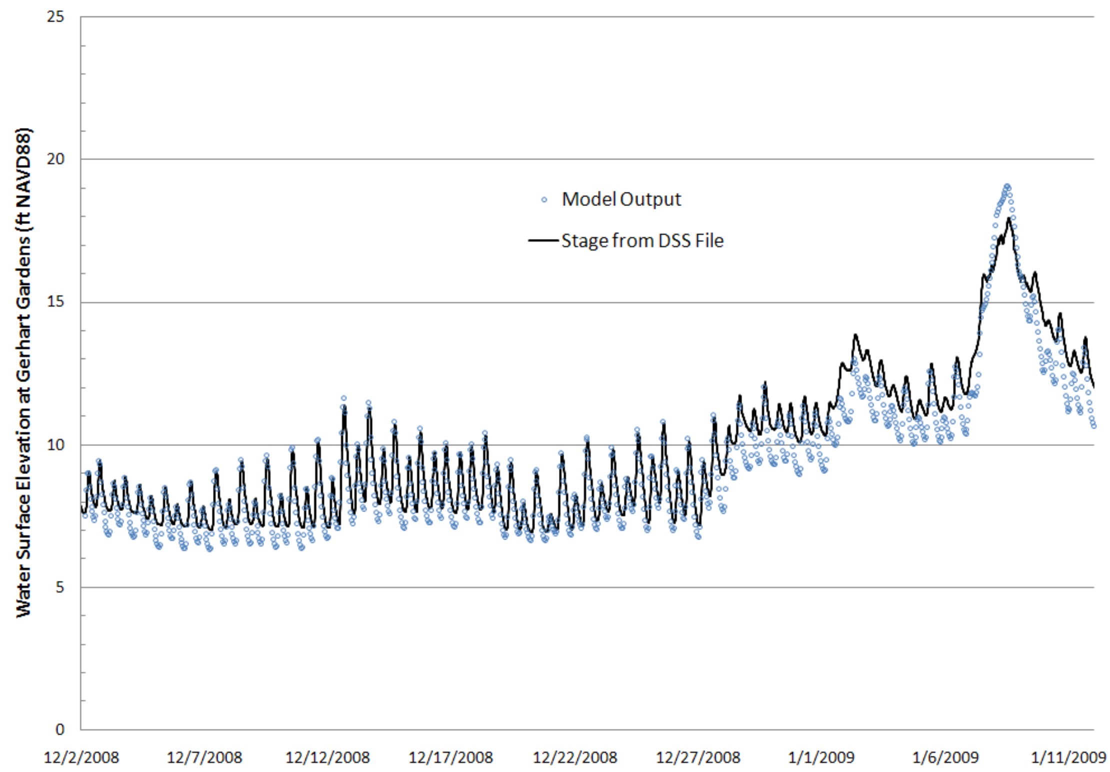

Figure 5.27 Lower Cowlitz Model Verification Water Surface Comparison at Gerhart Gardens

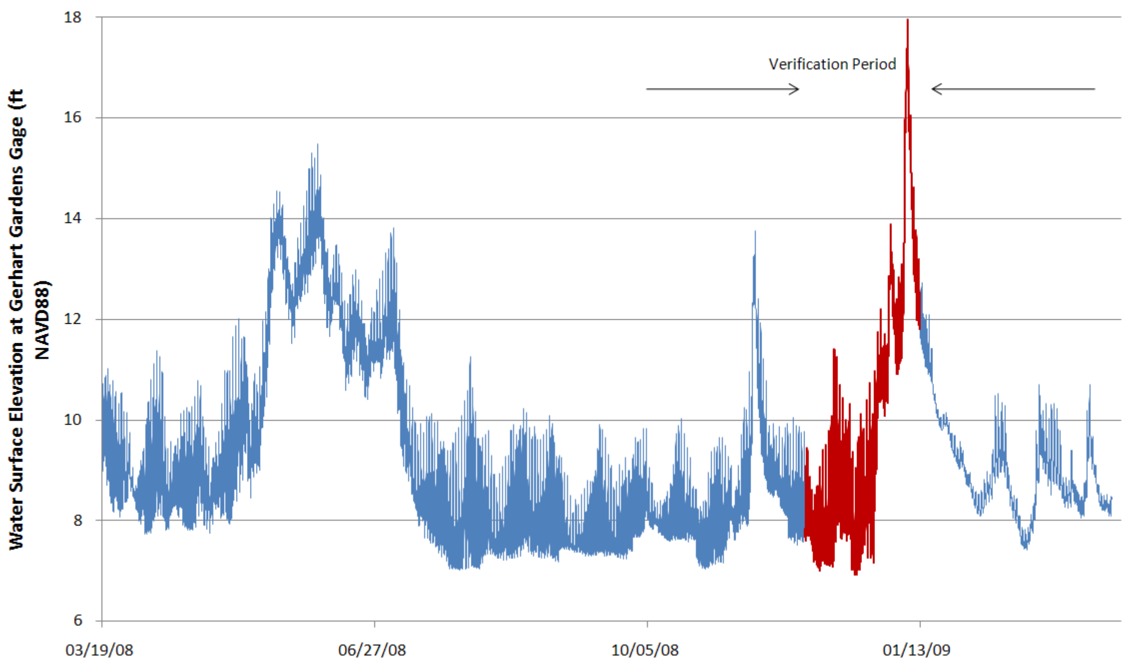

Figure 5.28 Lower Cowlitz Model Verification Period as Subset of Available Gerhart Gardens Stage Data

5.2.3 Results

The 3-year study period was incremented to better understand the response of the Lower Cowlitz River model reach to different inflow and boundary conditions and how the channel might evolve over time in response to changes in bed geometry, hydrology, and inflowing sediment.

The 2-D model was run for the Aug 2004 to Aug 2007 study period with the water and sediment inflow hydrographs and Columbia River water surface elevation vs. time relationship as described in the preceding sections. Results are presented below for each year of this series and for the entire study period.

Aug 2004 to Aug 2005

The first year of the model study has the lowest average Cowlitz River inflow (7,025 cfs), the lowest average Columbia downstream water surface elevation (7.5 ft), and the lowest peak Cowlitz flows and sediment inflow. A plan view of the change in Cowlitz River bed geometry after modeling the period from Aug 2004 to Aug 2005 is shown in Figure 5.29.

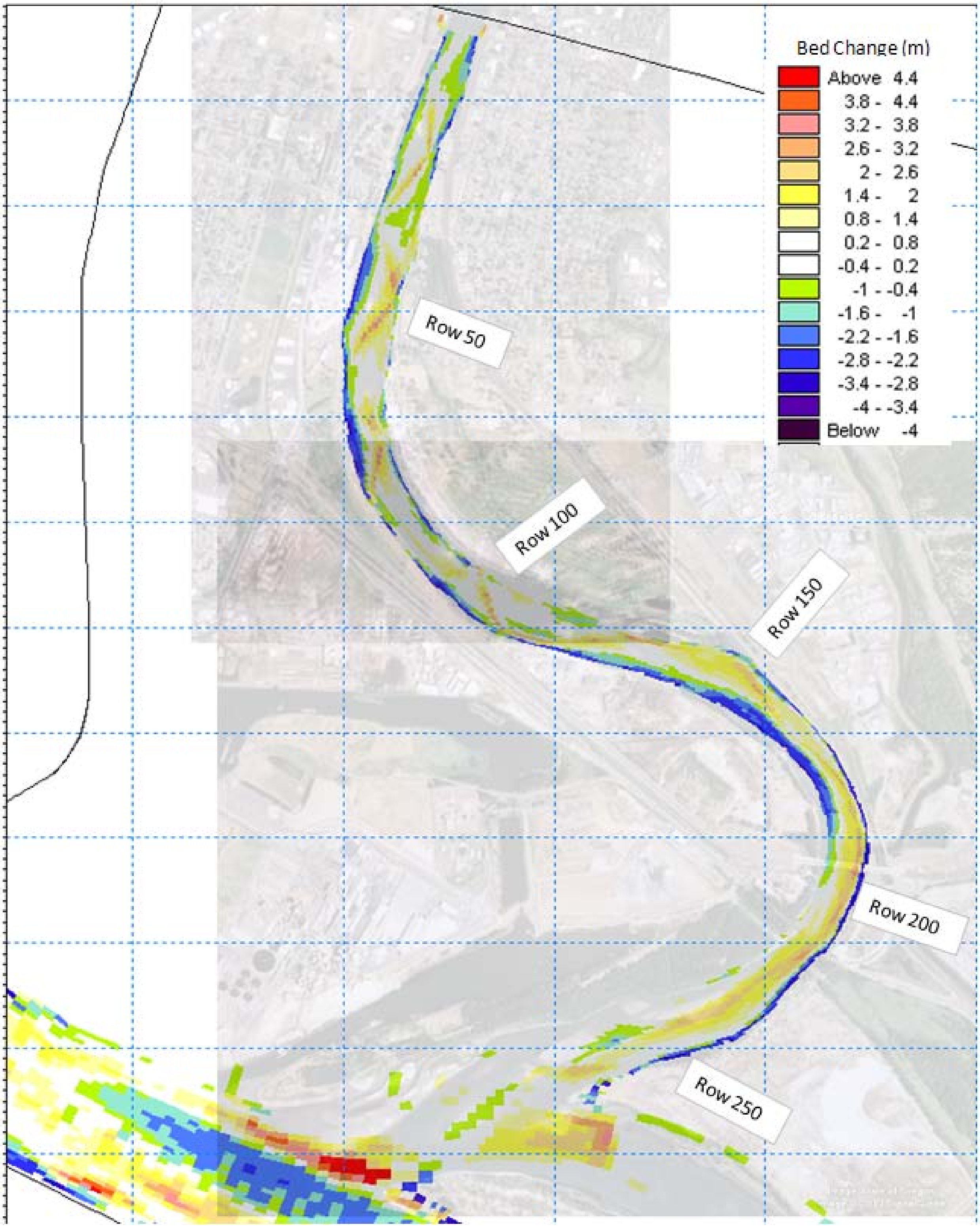

Figure 5.29 Lower Cowlitz Model Bed Change between Aug 2004 and Aug 2005

If the study area is considered from upstream to downstream in a row-wise manner, there are areas of deposition (yellow and red coloration) and scour (green and blue coloration) from Row 0 to about Row 200. The solid blue line in Figure 5.33 illustrates the net trend of accumulated deposition and scour for this period. Accumulating net change per row in an upstream to downstream progression is one way to quantify changes to the channel throughout the study reach over time. Flat parts of the line indicate little change (deposition or scour), while the upward trend shows that the study reach becomes depositional from about Row 200 to the confluence of the Cowlitz and Columbia Rivers. The period from Aug 2004 to Aug 2005 results in about 830,000 tons of deposition in this area. The plan view (Figure 5.29) shows an increasing amount of depositional channel change in the area downstream from Row 200.

Aug 2005 to Aug 2006

The resultant bed geometry from the previous step (Aug 2004 to Aug 2005) was used along with the appropriate inflow and boundary conditions for the next year to generate output for the Aug 2005 to Aug 2006 period. This period has a higher average Cowlitz River inflow (9,250 cfs), the highest average Columbia River downstream water surface elevation (8.6 ft), and a medium-sized peak with a higher baseflow in the Cowlitz. A plan view of the change in Cowlitz River bed geometry for this model period is shown in Figure 5.30. The entire study area is net-depositional during this modeled year. An increase in sediment and water input to the system is noticeable during this study year; the resulting accumulated row-wise sedimentation are shown with the red line representing Aug 2005 to Aug 2006 in Figure 5.33. This year is the highest period of deposition. About 3.4 M Tons of material is predicted to settle within the study reach in the Aug 2005 to Aug 2006 model period.

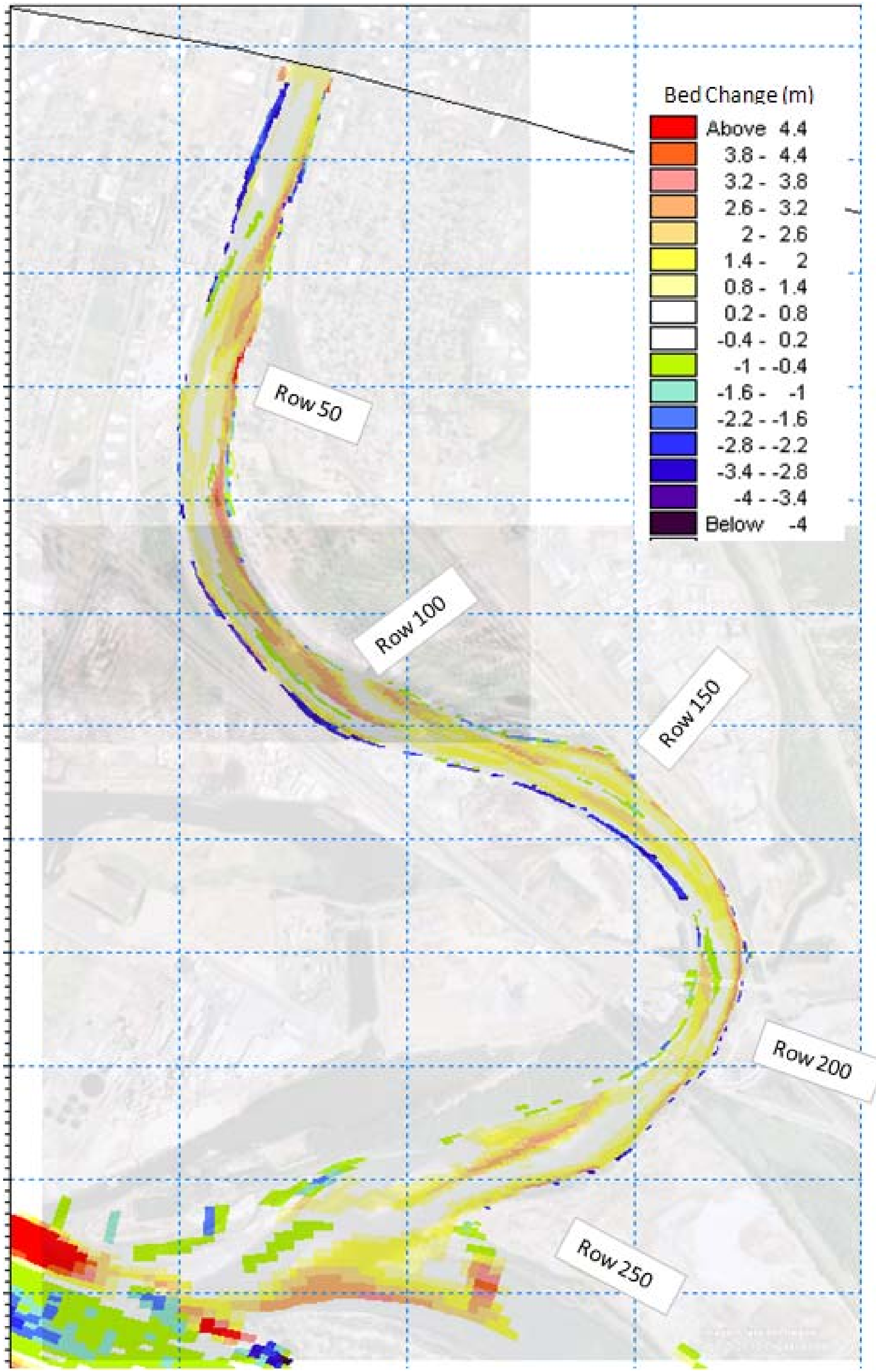

Figure 5.30 Lower Cowlitz Model Bed Change between Aug 2005 and Aug 2006

Aug 2006 to Aug 2007

The third year of the modeling period used the bed generated from the Aug 2005 to Aug 2006 period along with the remainder of the boundary condition hydrographs, stage, and sediment inflow curves. This year has the highest average Cowlitz River inflow (10,200 cfs), an intermediate average downstream Columbia River water surface (8.0 ft), and the biggest spike in Cowlitz River inflow and sediment inflow of the three study years. Interestingly, Figure 5.31 shows a slightly degradational trend in most of the model reach for this year. The green line in Figure 5.33 shows that by row, this model year is scouring most of the channel that had built up during the highly depositional Aug 2005 to Aug 2006 period. The last few rows begin to deposit some material, but for the most part, this year serves to regenerate the conveyance channel that was filled in significantly in the previous year. Total deposition in the Cowlitz River from this study year is on the order of 360,000 tons.

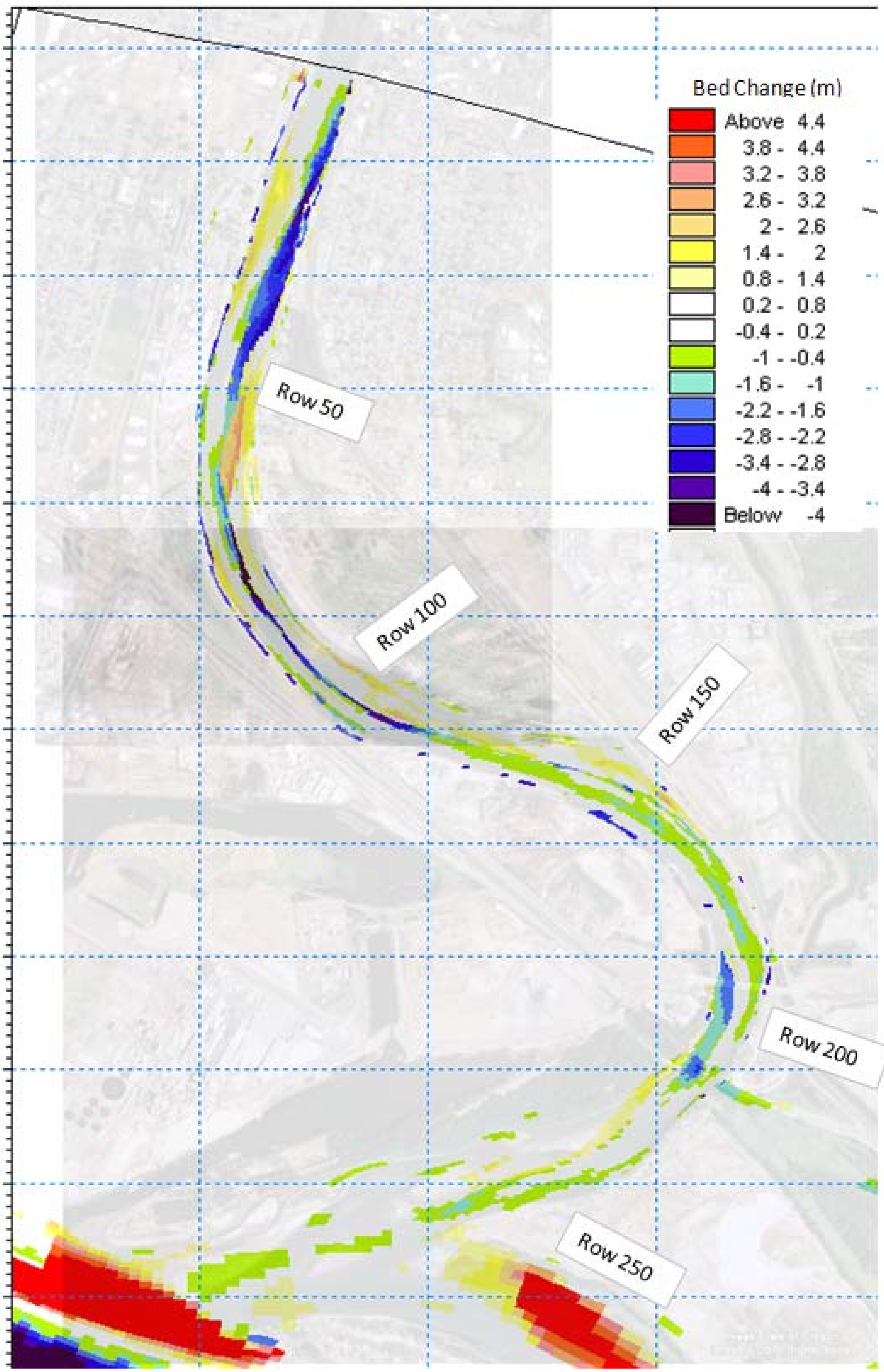

Figure 5.31 Lower Cowlitz Model Bed Change between Aug 2006 and Aug 2007

Aug 2004 to Aug 2007 (3 years combined)

The previous sections presented each of the 3 years in sequence, but individually to gain some insight into the chronology of sedimentation and time-wise channel evolution. If the entire 3-year run is summarized, then the total bed change from the beginning of the run to the end (Aug 2004 to Aug 2007) can be seen in Figure 5.32. This plan view shows the additive effect of combining the three incremental changes from Figure 5.29, Figure 5.30, and Figure 5.31. Another way to look at the change in character of the study reach over the 3-year period is to see the black and blue dashed line in Figure 5.33. This line is the sum of each of the individual yearly changes, which shows that for this 3-year period the model reach is almost entirely depositional and that about 4.5 M Tons of material is expected to deposit in this area.

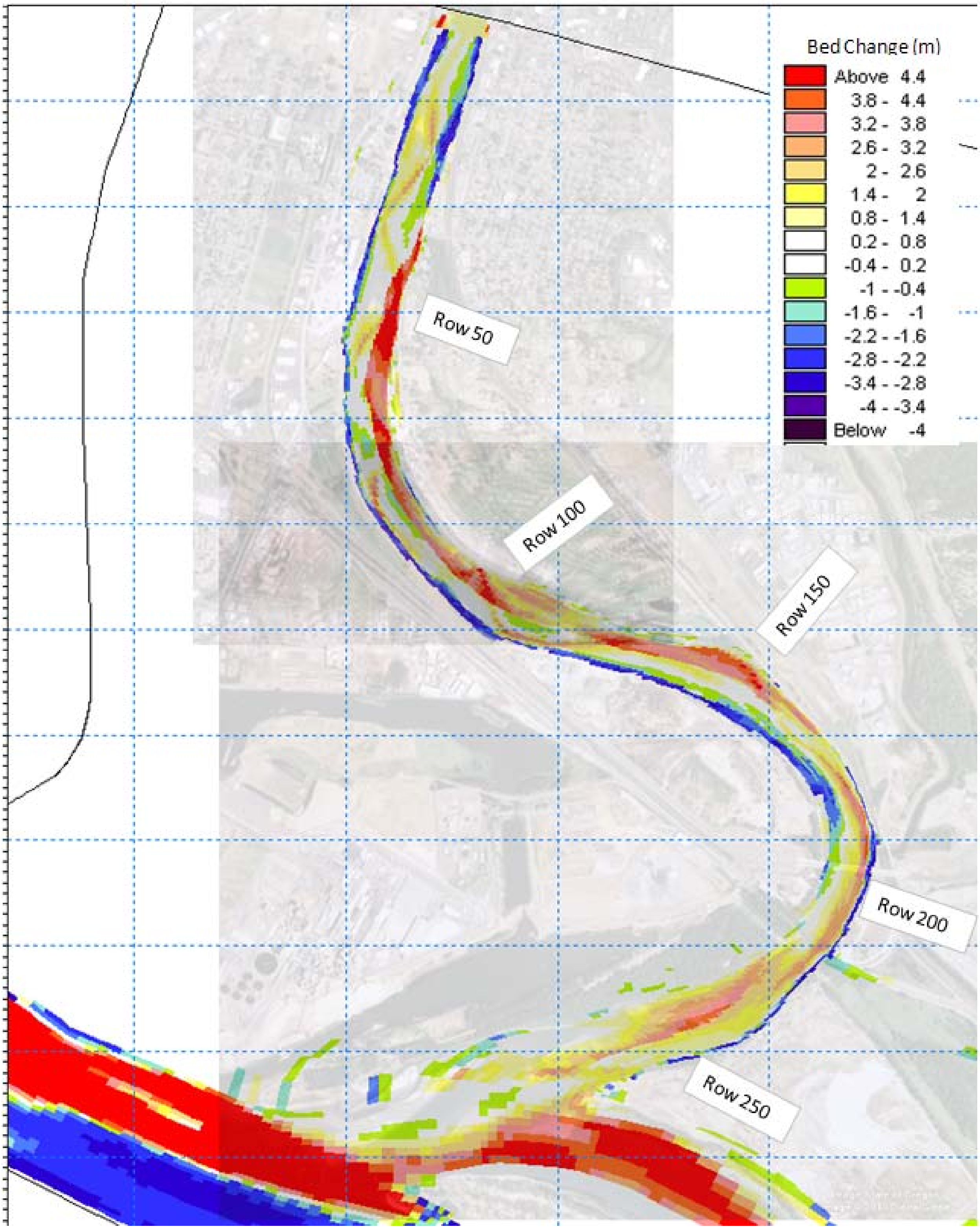

Figure 5.32 Total Model Bed Change at the End of the Third Year (Aug 2004 to Aug 2007)

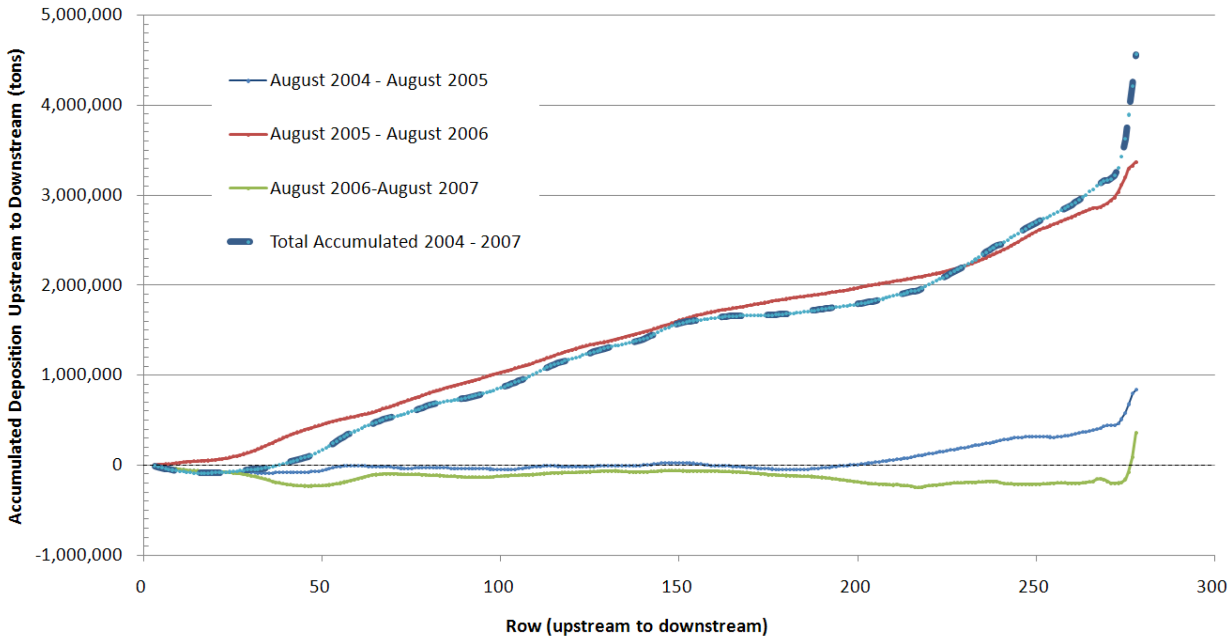

Figure 5.33 Lower Cowlitz Model Accumulated Row-wise Channel Change from Upstream to Downstream

5.2.4 Summary

The Lower Cowlitz River 2-D model study used temporally varying water and sediment inflow along with a tidal boundary on the Columbia River to simulate channel response and sedimentation for the area over a representative 3-year period. The same model will be used in the future to model alternative sediment management strategies within this reach and changed sediment inflow resulting from different upstream alternatives. Comparing the model output between sediment management alternatives will provide decision support for measures, which will address sedimentation issues in this area.

For the 3-year study period, the only time when the system was not depositional was after the first large sediment inflow from the Aug 2005 to Aug 2006 period. The high average and peak flows in the Aug 2006 to Aug 2007 period resulted in a small amount of clearing of the upper part of the model reach for the last year modeled (some of that material settled in the lower model rows). The results are similar to those of the 2-D model upstream from the SRS where large periods of deposition tended to be followed with either periods of slower sediment plain growth or some degree of sediment plain erosion.

6.0 PERFORMANCE METRIC

The USACE was directed by Congress to maintain an authorized LOP for four leveed communities along the Cowlitz River that is not less than described in the 1985 Decision Document (USACE 1985). These levees are the Castle Rock Levee (RM 16.1 to 17.6), Lexington Levee (RM 7.0 to 9.6), Kelso Levee (RM 2.6 to 6.8) and Longview Levee (RM 3.1 to 5.5). The authorized LOPs are shown in Table 6.1. The Water Resources Development Act of 2000 (Congress of the United States 2000) authorized the USACE to maintain these LOPs through the end of the MSH Project planning period (through 2035).

Table 6.1 Authorized Levels of Protection

Levee Location	Levee Length (miles)	Authorized LOP % Chance Exceedance	Average Annual Recurrence Interval (years)
Castle Rock	1.5	0.85	118
Lexington	2.7	0.60	167
Kelso	5.7	0.70	143
Longview	2.4	0.60	167

The most recent USACE LOP analysis reflects the observed conditions in WY 2009 using a probabilistic approach as described in *Risk Analysis for Flood Damage Reduction Studies* (ER 1105-2-101; USACE 2006b). The 2009 study includes new hydrologic, hydraulic, and levee fragility studies. At the time of the 2009 Report, all levees were very near or above their authorized LOP. The 2009 LOP Report (USACE 2009b) and subsequent geotechnical memorandums provide the backbone for the project performance metric described in this section.

It is desirable to have the project performance metric relate directly to the Congressional authority. With the suite of models described in this report it is possible to produce a probabilistic levee performance metric for future conditions with and without alternatives. The models can be used to predict future condition stage-discharge rating curves for frequency flows. This can be combined with the existing hydrologic and geotechnical data and analyzed in the Flood Damage Assessment (FDA) tool. Where this future approach separates from an actual level of protection (or conditional non-exceedance probability) analysis is with uncertainty. Actual estimations of uncertainties in future conditions would quickly dissolve the analysis given the level of uncertainty with this project.

The approach utilized here is to use hydrologic analysis and hydraulic uncertainties from the 2009 LOP Report and the most recent levee fragility curves. The only changes in the FDA

analysis for the future conditions are with the stage-discharge rating curves at each index point. While this approach does not attempt to predict actual future levels of protection it is very useful for determining equivalence of alternatives by providing a common probabilistic-based approach relying on modeling output. While a deterministic relevant water surface may provide much of the same comparison it would not be sensitive to changes in the rating curve shape or potential levee modifications.

To evaluate the effect deposition has on the water surface in the Lower Cowlitz, cross-section geometry was extracted at discrete times in the long-term 1-D simulation runs; 5-year intervals from 2010 through 2035. For each geometry extracted from the mobile-bed model, steady-state water surface profiles were generated using calibration factors from the 2009 LOP Report for the full range of frequency events. Rating curves were developed for each time frame at each levee index point and entered into the FDA to generate the probabilistic future performance.

Increasing deposition and increasing water surface elevation results in a reduction in levee protection in the future. Figure 6.1 shows this reduction of protection for each of the authorized levees along the lower Cowlitz. The Keslo protected area is split into North Kelso and South Kelso as the two areas are hydraulically separated by natural high ground. The authorized LOP for each protected area is shown as a horizontal line along with the estimated probable future performance for each levee out to 2035.

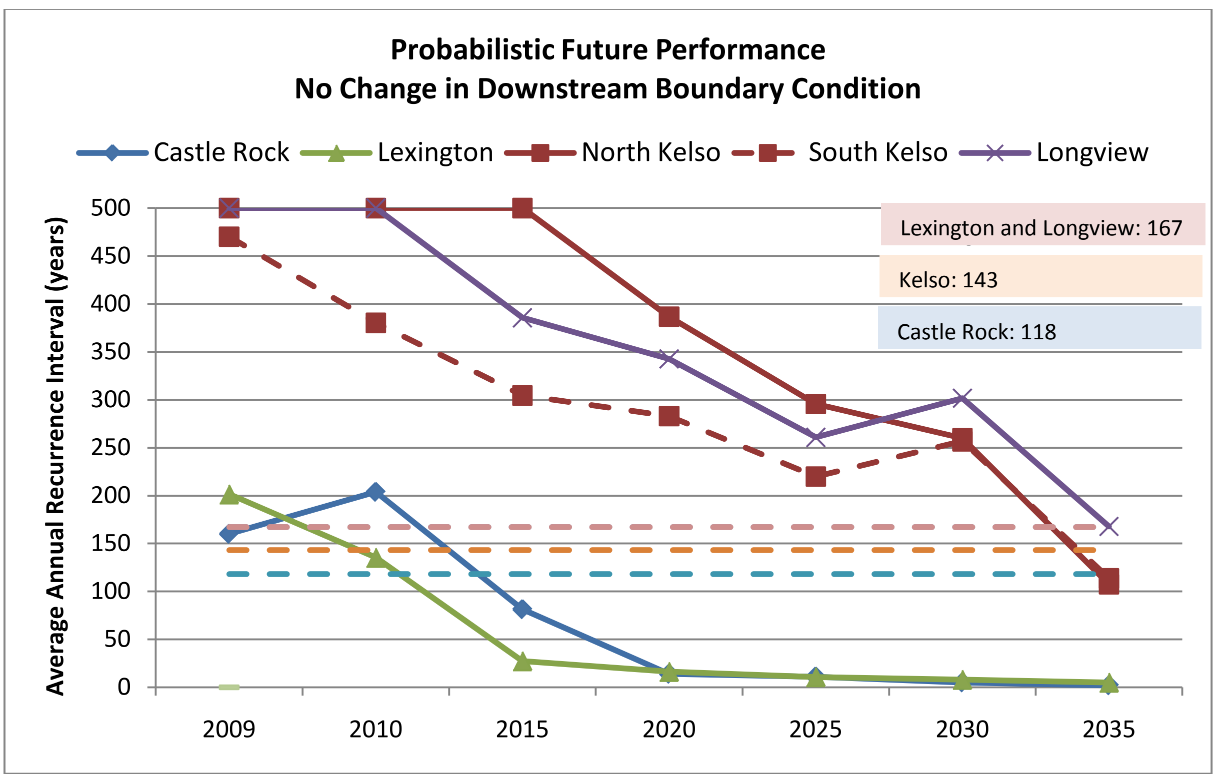

Figure 6.1 Probabilistic Future Performance (no change in downstream boundary condition)

The downstream boundary condition utilized in the FDA to create Figure 6.1 is constant in time and equal to that used in the 2009 LOP Report. This boundary condition is generated by analysis of the NOAA gage located along the Columbia River in Longview and fairly represents conditions in the Columbia. Since the 1-D model of the Cowlitz does not extend into the Columbia, all shoaling that could affect water surface elevations in the Cowlitz is not captured in the mobile-bed model. The mouth of the Cowlitz has been observed as a high deposition zone historically, most recently experiencing a large shoal located at the downstream-most cross section in the 1-D model prompting the USACE to dredge the mouth of the Cowlitz in 2008. The downstream Cowlitz 2-D model can help inform on effect of shoaling at the mouth on flood frequency profile changes.

The 2-D model was run for a 3-year period with 1 year each of low, medium, and high flows/sediment loads. Frequency flows for the 100-year and 200-year events were run for the original geometry as well as the final geometry and the raise in water surface at the railroad bridge located at RM 1.35 was determined. The water surface stage delta for the 3-year run was +0.8 ft in both cases for an average rise of 0.27 ft/yr.

It is expected that the long-term trend in water surface rise would not be linear but would be concave. The Columbia River navigation channel is regularly maintained such that frequency stages in the Columbia River can be assumed to be stationary in time. As deposition continues into the future at the mouth of the Cowlitz, the hydraulic gradient between the Cowlitz and the Columbia will steepen. This steepening would result in higher velocities and presumably higher shear generally increasing transport capacity and decreasing deposition. Without the ability to model the confluence for a much longer period of time, the extent of this theoretic reduction is unknown.

For this reason, the average annual change in downstream water surface is estimated at a consistent 0.15 ft/yr through the simulation period starting in WY 2010. This rise will be applied consistently to all frequency flows as shown in Table 6.2. The downstream boundary condition for the future 1-D steady-state models will be adjusted accordingly before running frequency flows. Rating curves from these model runs will be used in the FDA analysis for future years. Figure 6.2 shows the effects of the rising downstream boundary condition on probabilistic future performance at the authorized levees on the Lower Cowlitz.

Table 6.2 Downstream Boundary Conditions Reflecting Shoaling at Mouth of the Cowlitz

Flood Annual Event Probability	*Q* Total (cfs)	Downstream Boundary Condition (ft-NAVD88)					
		2010	2015	2020	2025	2030	2035
99.99	10,000	10.81	11.56	12.31	13.06	13.81	14.56
99	11,000	11.05	11.80	12.55	13.30	14.05	14.80
95	18,000	12.05	12.80	13.55	14.30	15.05	15.80
90	24,000	12.65	13.40	14.15	14.90	15.65	16.40
80	32,000	13.45	14.20	14.95	15.70	16.45	17.20
70	36,500	13.90	14.65	15.40	16.15	16.90	17.65
60	41,000	14.43	15.18	15.93	16.68	17.43	18.18
50	46,000	15.05	15.80	16.55	17.30	18.05	18.80
40	51,000	15.57	16.32	17.07	17.82	18.57	19.32
30	58,000	16.25	17.00	17.75	18.50	19.25	20.00
20	66,000	17.05	17.80	18.55	19.30	20.05	20.80
10	80,000	18.27	19.02	19.77	20.52	21.27	22.02
5	96,000	19.45	20.20	20.95	21.70	22.45	23.20
4	100,000	19.80	20.55	21.30	22.05	22.80	23.55
2	108,000	20.87	21.62	22.37	23.12	23.87	24.62
1	113,000	21.50	22.25	23.00	23.75	24.50	25.25
0.7	117,000	22.07	22.82	23.57	24.32	25.07	25.82
0.5	124,000	22.60	23.35	24.10	24.85	25.60	26.35
0.2	160,000	24.05	24.80	25.55	26.30	27.05	27.80
0.1	190,000	25.05	25.80	26.55	27.30	28.05	28.80
0.08	210,000	25.37	26.12	26.87	27.62	28.37	29.12
0.05	300,000	26.05	26.80	27.55	28.30	29.05	29.80
0.01	390,000	28.37	29.12	29.87	30.62	31.37	32.12

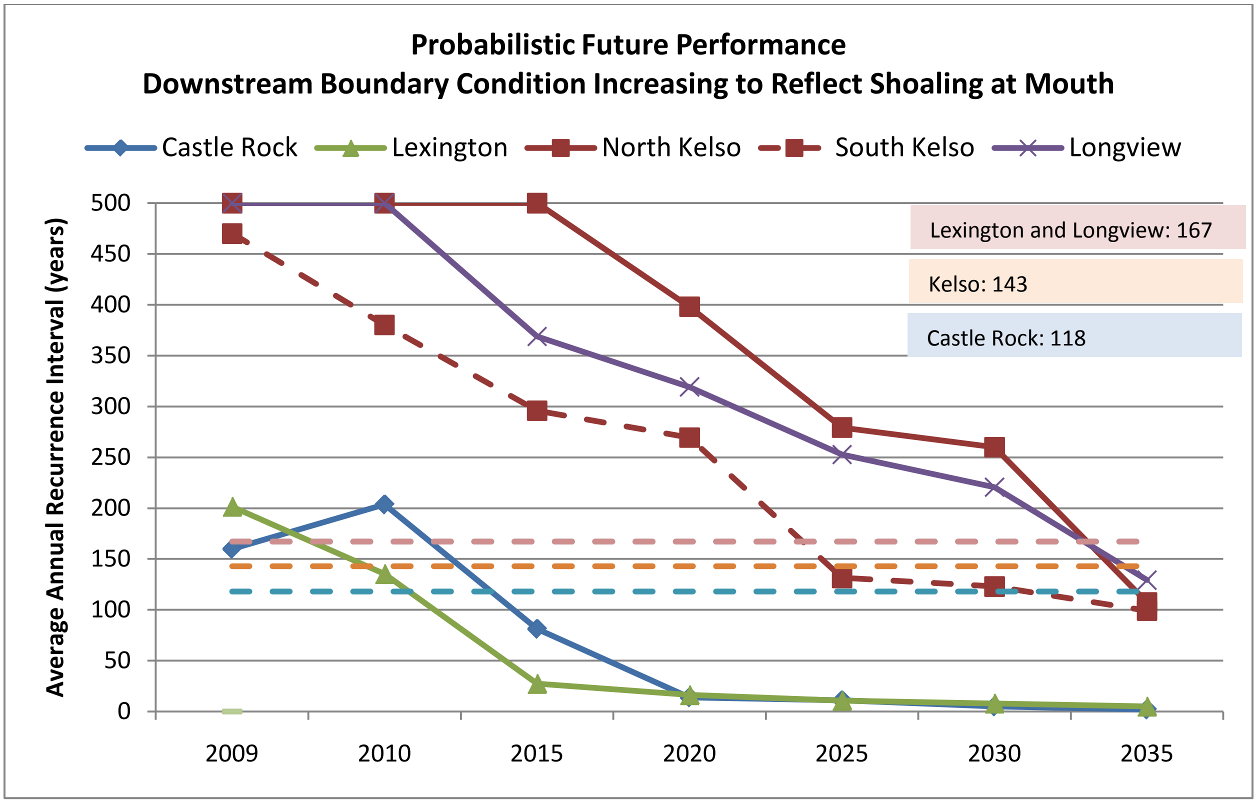

Figure 6.2 Probabilistic Future Performance (downstream boundary condition increasing to reflect shoaling at mouth)

Figure 6.1 and Figure 6.2 show that the deposition in the Lower Cowlitz has the most profound impact on future performance of the upstream levees in the system, Castle Rock and Lexington. The deposition in these areas, consisting of coarser materials, causes significant increases in water surface elevation and reduction in the protection provided by the respective levees. Further downstream in the system, the Kelso and Longview levees appear to provide adequate levels of protection for some time. Increasing the downstream boundary condition at the rate described above effects the Longview and South Kelso levees only. The boundary condition effect does not extend upstream to North Kelso or above in the system. All levees experience a significant drop in performance by the end of the simulation.

2009 actual values are shown along with predicted 2010 values. Variation between 2009 and 2010 is largely due to establishment of the mobile-bed model active layer during the beginning of the long-term model run with finer sediment eroding from the upper reaches and settling in the lower reaches. Both years are presented to demonstrate the magnitude of unavoidable model error associate with the method. The probabilistic method employed by FDA is very sensitive to small changes in input parameters. It is a testament to the modeling scheme that this approach provides reasonably accurate data. The trends determined by the analysis are more reliable than the absolute values; however, the absolute values are felt to be accurate enough to determine parity between alternatives during alternative analysis.

This probabilistic future performance metric will be used to determine if a proposed action or suite of actions (alternative) is viable in protecting the communities. Alternatives moving forward for consideration will need to reasonably meet the performance metric as described.

The following figures provide further intuitive understanding of the data being incorporated in the performance metric. 1% annual exceedance water surface profiles from 2009 through 2035 in 5-year increments are plotted along with top of levee and levee fragility index point probability bounds for each of the four protected communities (Figure 6.3, Figure 6.4, Figure 6.5, and Figure 6.6). For the controlling index point at each levee (the lowest performing index point along the levee for a protected area), the fragility curve probability bounds are plotted along with the 1% and 0.5% annual exceedance profile stages through 2035 (Figure 6.7, Figure 6.8, Figure 6.9, Figure 6.10, and Figure 6.11).

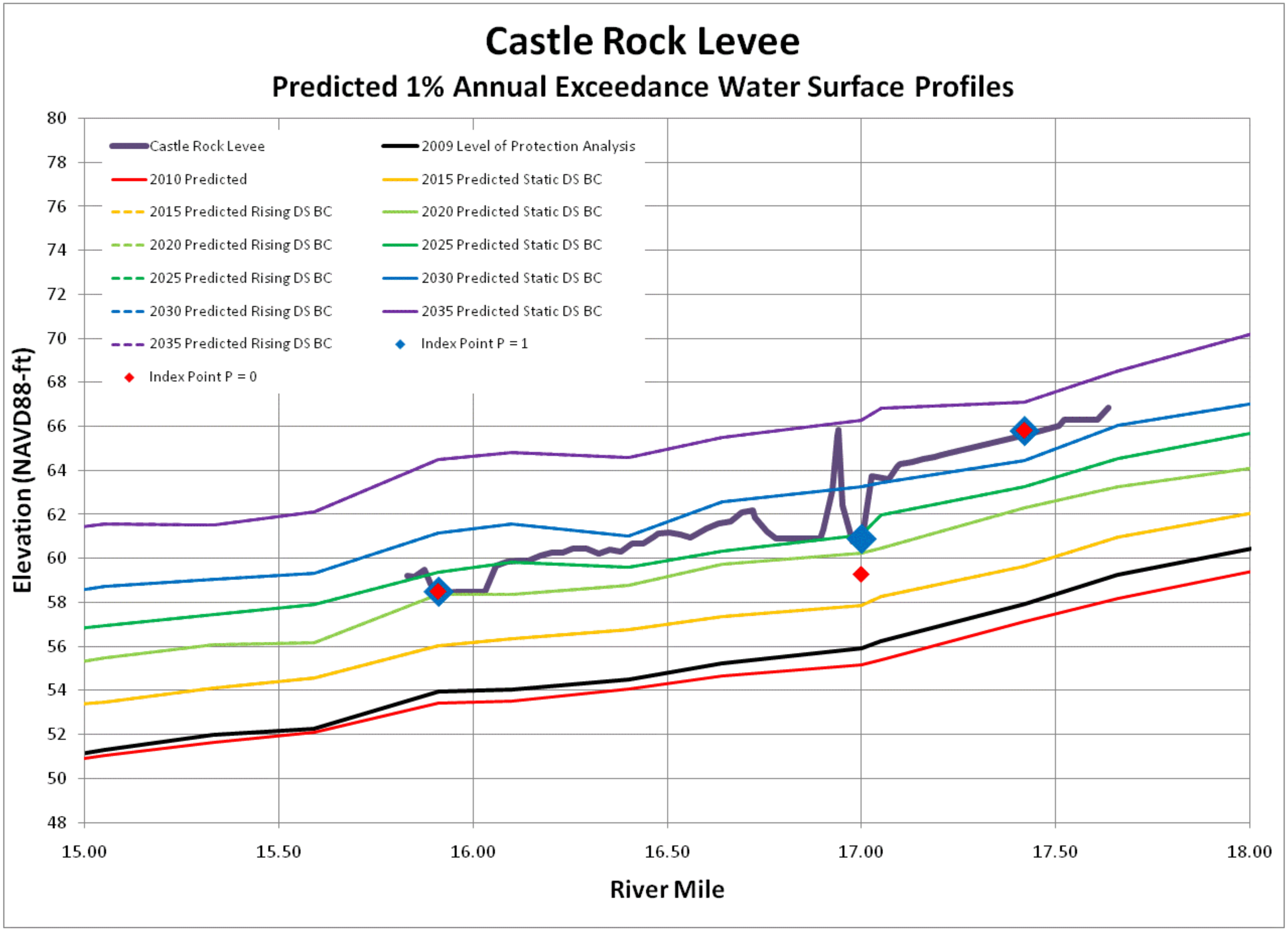

Figure 6.3 Predicted 1% Annual Exceedance Water Surface Profiles for Castle Rock Levee

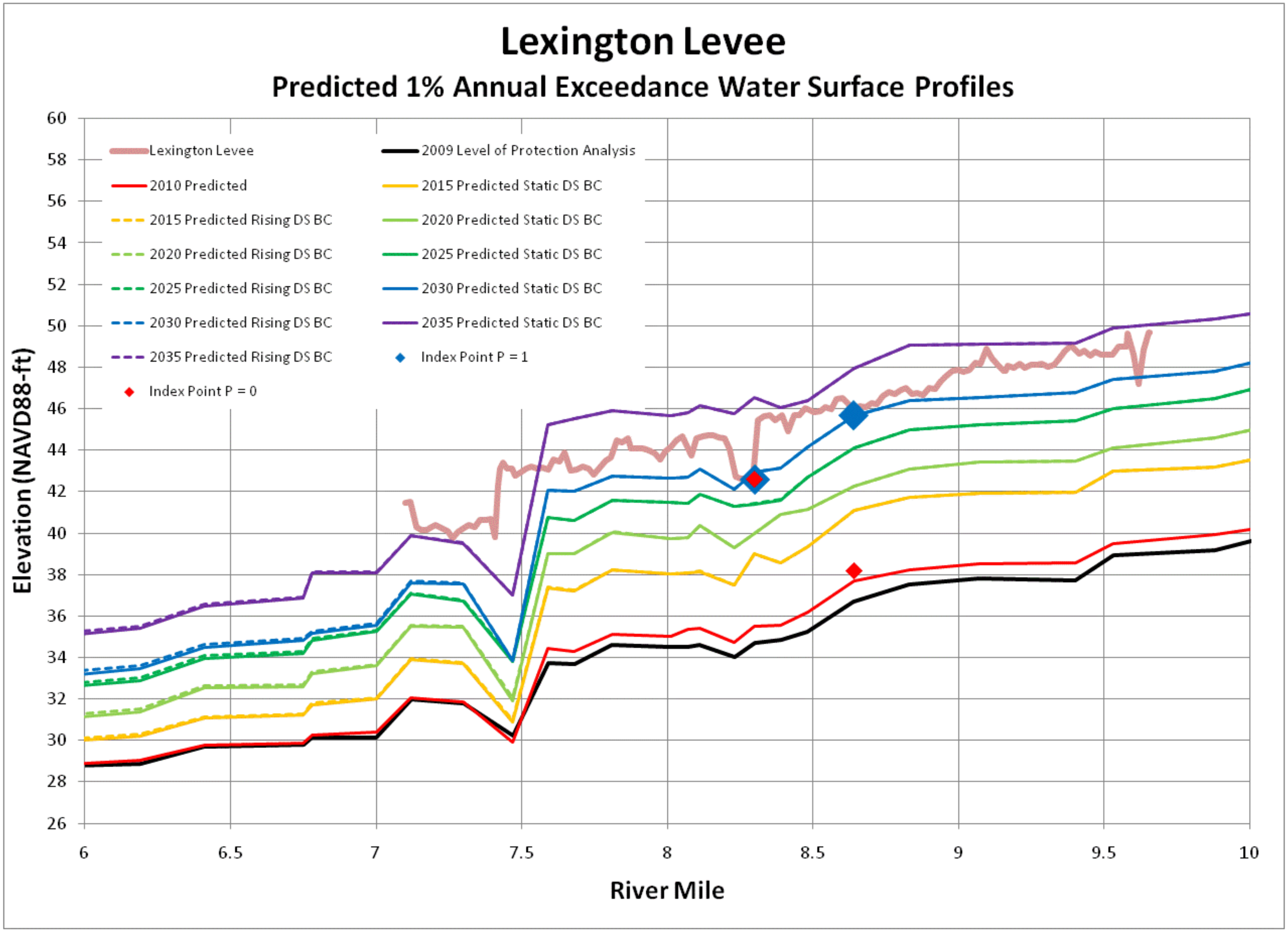

Figure 6.4 Predicted 1% Annual Exceedance Water Surface Profiles for Lexington Levee

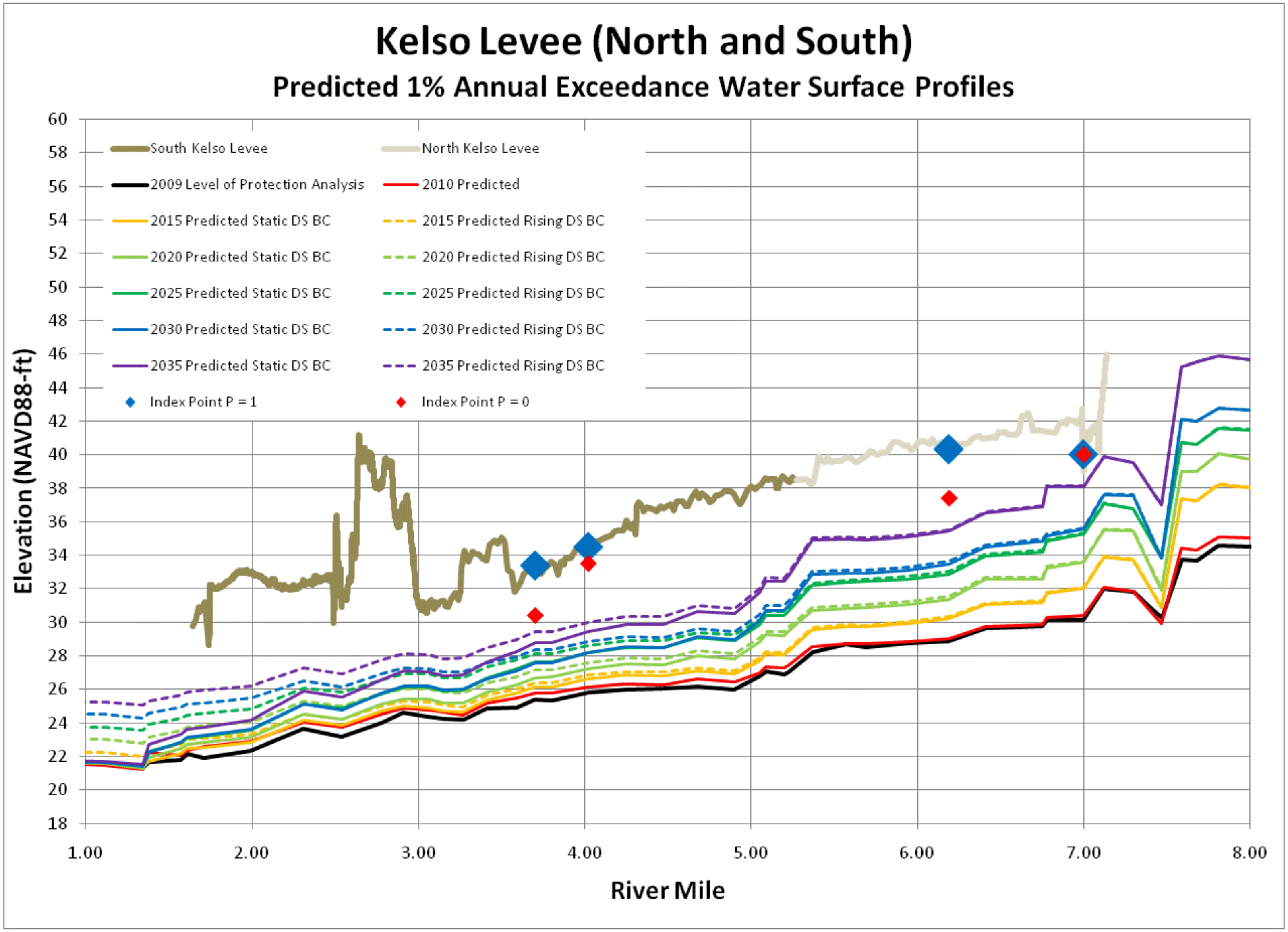

Figure 6.5 Predicted 1% Annual Exceedance Water Surface Profiles for Kelso Levee (North and South)

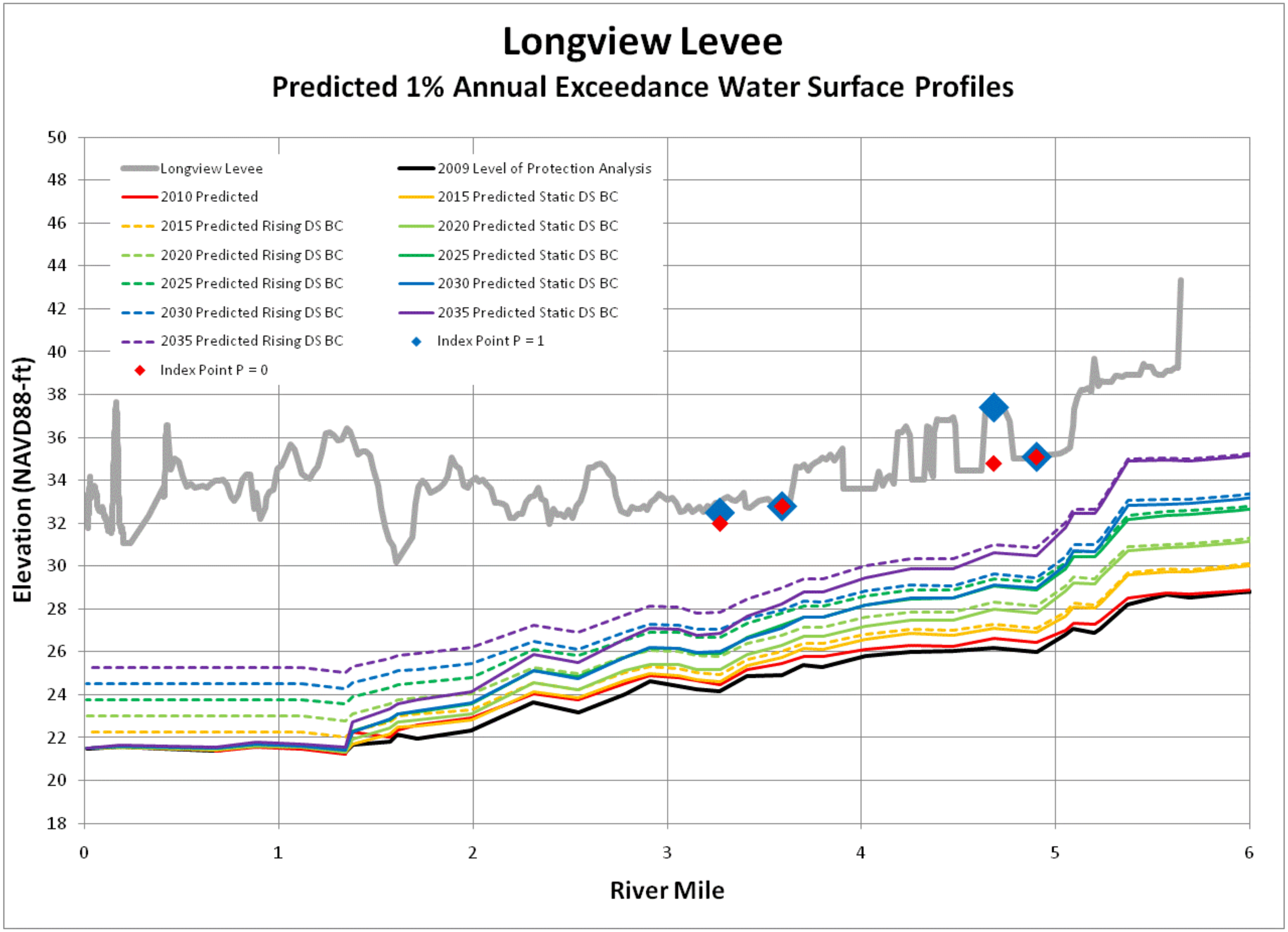

Figure 6.6 Predicted 1% Annual Exceedance Water Surface Profiles for Longview Levee

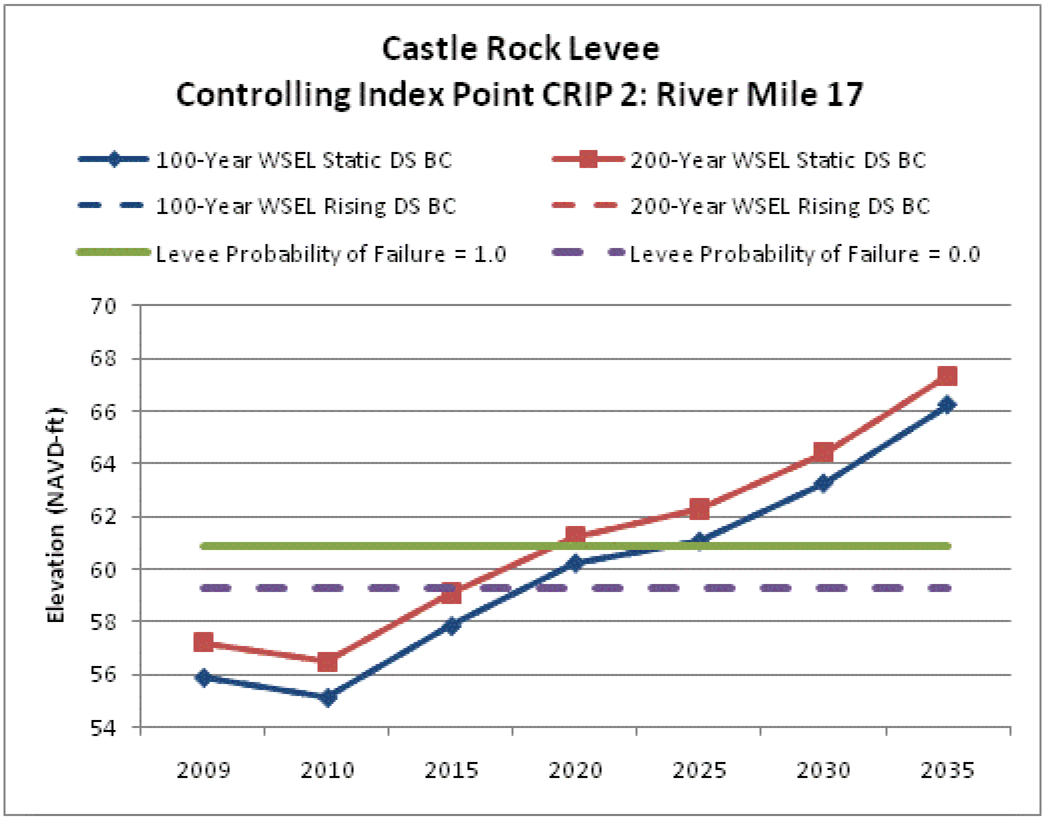

Figure 6.7 Controlling Index Point at Castle Rock Levee

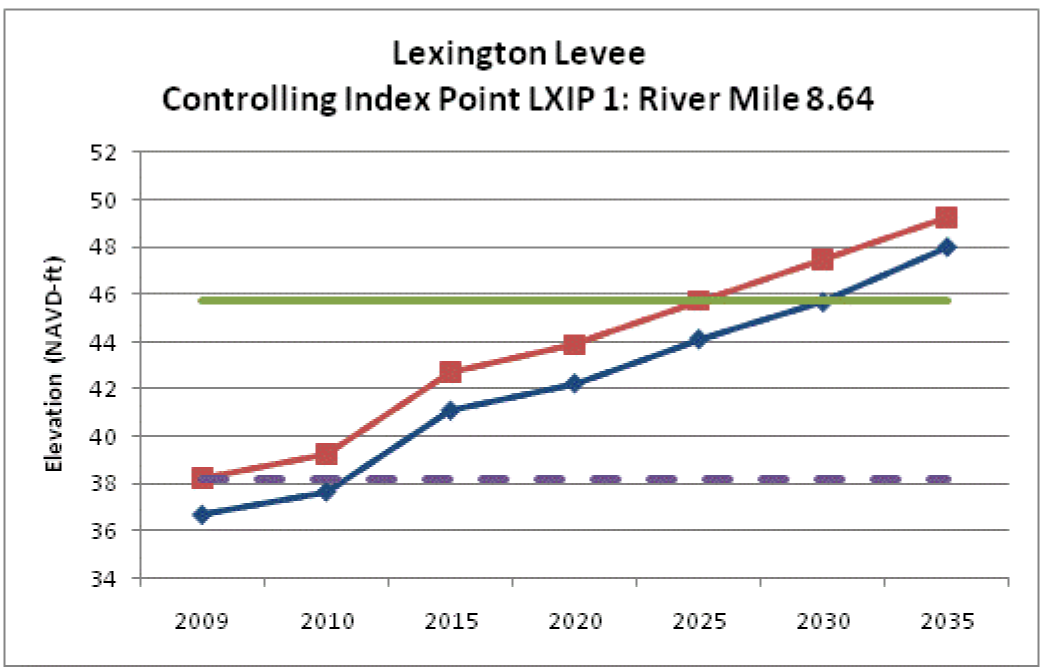

Figure 6.8 Controlling Index Point at Lexington Levee

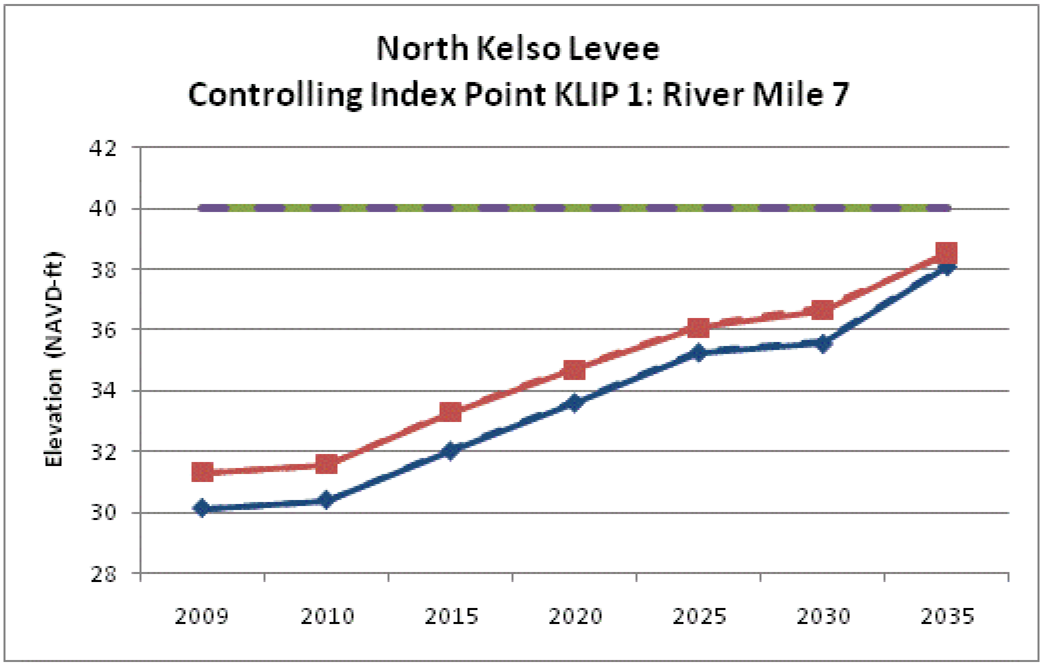

Figure 6.9 Controlling Index Point at North Kelso Levee

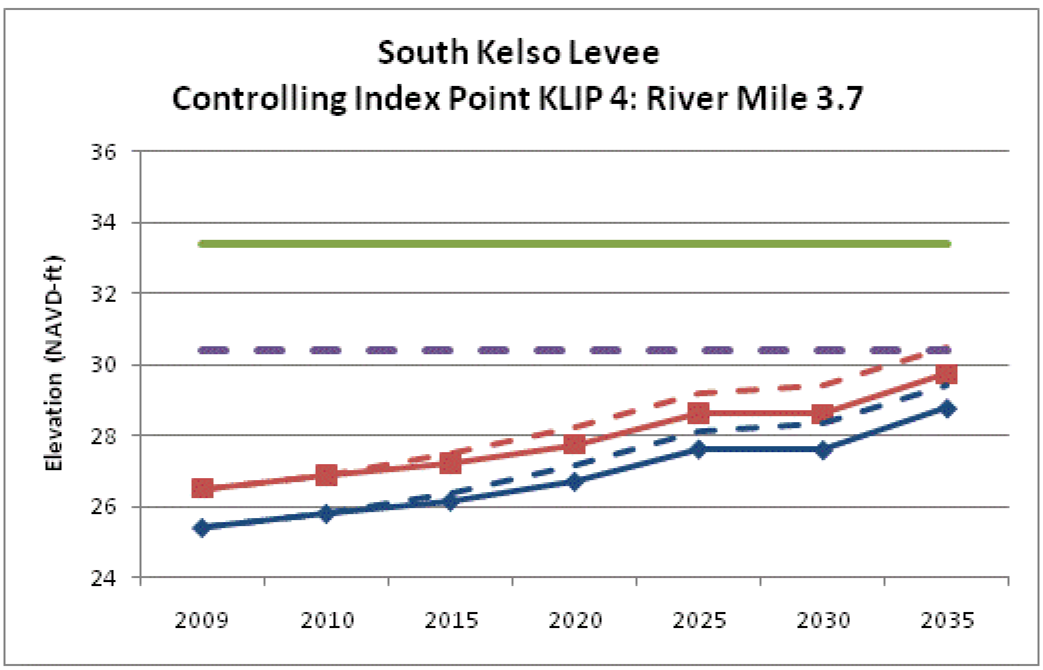

Figure 6.10 Controlling Index Point at South Kelso Levee

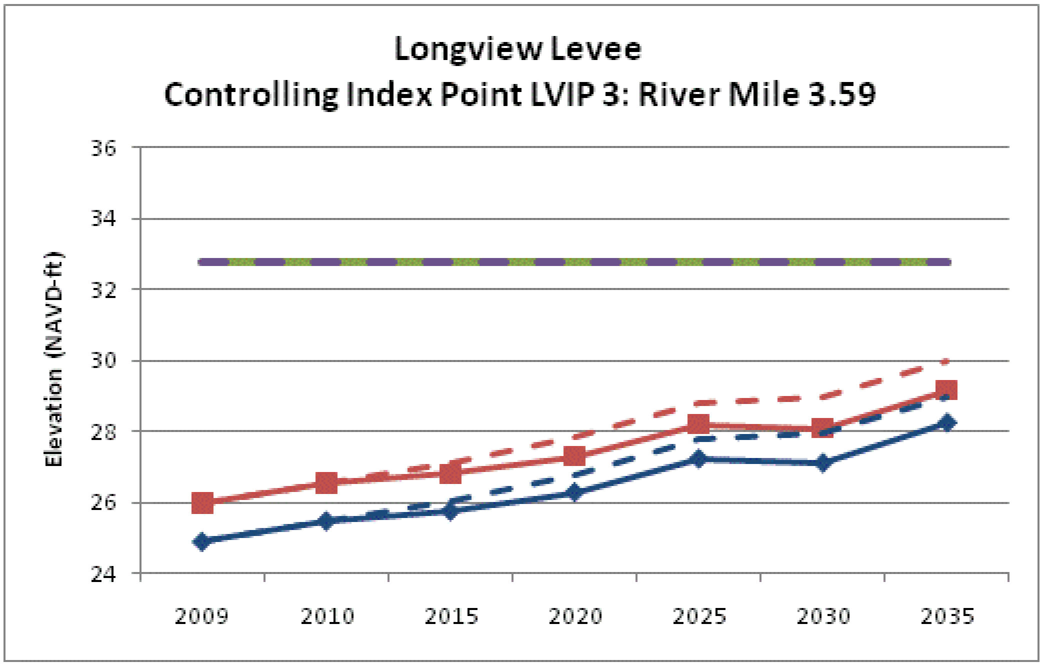

Figure 6.11 Controlling Index Point at Longview Levee

7.0 CONCLUSIONS

It should be clear to the reader that the FEDS does not pretend to predict the future in exacting detail. The goal of the FEDS is to gain additional understanding of the system and create a reasonable framework for comparison of alternatives through the end of the planning period. The hydrologic and sedimentation series used for future prediction is based on a historic data with an applied stationarity assumption and in no way should be considered an exact prediction of future events or event sequences.

Sedimentation studies, and mobile-bed modeling specifically, have always been understood to have high levels of uncertainty. Depositional and aggradational trends determined by modeling have traditionally been considered more accurate than absolute values. Similarly, results expressed in mass are more reliable than those expressed in volume given uncertainties with *in-situ* unit weights. The analytic scheme described in this report attempts to accurately determine trends within the system, but also necessarily relies on the absolute precision of the final results in realizing a performance metric for alternative analysis. Significant effort has been expended to calibrate the tools to the extent possible, understanding that this improbably achieved precision is vital to the analytic approach. Additionally, engineering judgment has been thoughtfully applied throughout the investigation to ensure that reported results match observed phenomena and intuition to the best of the team's and profession's abilities.

The approach taken lays the foundation for future plan selection determining alternative parity based on model results. Result quality needs to be such that competing alternatives can be compared without undue bias. The scheme must provide adequate flexibility to accommodate the full range of proposed actions, while delivering the required high-quality results. The models and subsequent scheme to integrate them into a complete system analysis described in this report are designed specifically for this task. Basic understanding of the system gained through the FEDS analysis stands as its own achievement regardless of future use.

Two major conclusions stand out from many learned and expressed in this document: 1) impacts of SRS performance decay and 2) timelines for communities at risk. Analysis of SRS future performance indicates that there will be a significant reduction in trapping efficiency of coarse and very coarse sands in the current planning period. Downstream analysis shows that these are the exact materials that compose the majority of deposition in the lower 20 miles of the Cowlitz in the same time frame. Any alternative must address these materials to be successful.

Uncontrolled deposition in the lower Cowlitz will affect upstream communities first. Deposition has a cumulative effect on flood stages in the lower Cowlitz, meaning that material deposited between RMs 0 and 15 can affect flood stages at RM 15, whereas flood stages at RM 5 are only affected by deposition between RM 0 and 5. Communities higher in the system will experience

a reduction in future performance more rapidly than those lower in the system due to this cumulative effect of deposition downstream of their levees. Addressing future performance at these upstream communities will require reduction in deposition through a large portion of the system below.

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